12-2009

DC Distribution with Fuel Cells as Distributed Energy Resources

Michael Starke
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Michael Starke entitled "DC Distribution with Fuel Cells as Distributed Energy Resources." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Electrical Engineering.

Leon Tolbert, Major Professor

We have read this dissertation and recommend its acceptance:

Fangxing Li, Hairong Qi, Charles Collins

Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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DC Distribution with Fuel Cells as Distributed Energy Resources

A Dissertation

Presented for the

Doctor of Philosophy Degree

The University of Tennessee, Knoxville

Michael Ralf Starke

December 2009

Dedication

This dissertation is dedicated to my loving wife. Her continued support and unconditional love have provided me enough energy and time to continue and finish my research.

This work is also dedicated to my parents, who have been beyond patient and have always been there when I needed them. Their love for their children is beyond any that I have ever witnessed.

Acknowledgments

I would like to thank all of the many people that have contributed to my education and research. The journey has been long, but memorable.

First and foremost, I greatly appreciate the contributions of my advisor, Dr. Leon M. Tolbert, for his instructions in class and on my dissertation work. His continued support even outside the realm of education and his gentle prodding to keep working have been instrumental in completion of this work. He is a great friend and mentor.

Many thanks to my committee members, Dr. Fangxing "Fran" Li, Dr. Charles Collins, Dr. Jack Lawler, and Dr. Hairong Qi for reading my work and providing invaluable suggestions and comments.

Special thanks to my co-workers at Oak Ridge National Laboratory, Burak Ozpineci and Travis Smith. Their knowledge, support, and leniency were crucial in my completion.

Finally, I would like to thank all of my friends, who were able to break me away from my work on the occasion and enjoy life.

Abstract

In recent years, the idea of a direct current (DC) distribution systems has returned to the public eye as a result of DC based energy sources. The battle between alternating current (AC) and DC began with Thomas Edison and George Westinghouse long ago with AC becoming the victor as a result of the transformer. However, development of power electronics and switching devices and DC based energy sources such as fuel cells has forced the reevaluation of DC systems. This dissertation is focused on once again addressing this topic, but with an examination of the technologies as they stand today. Along with examining basic efficiency of the competing technologies, distributed generation has as well peaked the interest and will be incorporated into the analysis. Optimum placement of this distributed generation (DG) source is vital to obtain the maximum benefit and techniques for optimization are examined. The sensitivity and "rules of thumb" for placement of DG in a DC system are developed. Last, the largest driving factor for system changes is cost. A brief examination of the economic factors that have the potential to drive DC systems is examined.

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1 INTRODUCTION

Pollution and carbon dioxide emissions have been attributed to many harmful effects including global warming, the acidification of rain (which contributes to substantial damage to buildings, harvests, and local ecosystems), and health related diseases. Renewable energy sources are expected to curtail these problems through energy sources that mitigate pollution and furnish energy security [1-3]. Although fuel cells are not considered to be renewable energy resources, as they require hydrogen, they still show tremendous promise as energy sources due to their high efficiency, the potential inexhaustible supply of fuel, low emissions, and their compatibility with renewable energies while having no restrictions on location. These assets have registered much attention to fuel cell technology and the inclusion of fuel cells into the distribution system [4, 5].

The Oak Ridge National Laboratory (ORNL) has strived to be one of the leading laboratories in the United States, if not in the world, in terms of energy research. To achieve this goal, alternative energies such as solar, wind, and fuel cells are constantly investigated for merit. As one avenue of research, ORNL is researching the benefits of applying fuel cells as distributed generation (DG) sources in their distribution network. For this reason, attention has been brought to the effectiveness of the current distribution system in utilizing these renewable energy sources.

1.1 DC Distribution System

The existing distribution system is based on alternating current (AC), but an overwhelming portion of the renewable energy sources, in particular fuel cells, produce direct current (DC). This substantiates the application of power electronic (PE) devices to convert the DC energy from the renewable sources to AC for transmission and distribution. Yet, this can induce considerable losses into the distribution system, reducing the acceptance and impact of renewable energy. Furthermore, a significant portion of loads now within buildings are DC, demanding more PE devices to reconvert the AC to DC. In progressing to eliminate the high quantity of converters, the idea of a DC distribution system for the ORNL distribution system spawned.

Nonetheless, elimination of converters is not the only asset that DC distribution has to offer. Since DC power is purely real, the inductive and capacitive elements of the distribution line can be ignored, condensing the complexity of calculations for system analysis. Moreover, these reactive components have been linked to an increase in the magnitude of current ensuring the depreciation of real power transmission and magnifying losses. DC distribution likewise promotes energy conservation through moderation of standby losses. The PE devices implemented in power converters have the capability to deactivate when not needed whereas the transformer conducive to AC systems must remain energized. The distribution system should further profit from DC through improved stability as synchronization would no longer be necessary. Synchronization of generation and load sources are mandatory in AC.

A DC distribution system is not a new concept. Thomas Edison first applied DC distribution during the period upon which electricity was first established. Yet, at that time no method existed for boosting the voltage in DC, and the transmission system suffered from low efficiency and variable voltage. This forced electric loads to be within close proximity of the generation source.

Nevertheless, an entirely new system of transporting electricity, AC, followed. L. Gaulard and J. Gibbs developed the transformer and ac transmission system to combat the problems of low voltage transmission. Through the use of a transformer, AC could be boosted or lowered resulting in high efficiency in transmission and a relatively fixed voltage independent of the location of the load. Nikola Tesla further advanced AC through the development of polyphase systems and the ac motor. These motors were much simpler and cheaper in design than the dc equivalent. Finally, George Westinghouse secured the rights to the transformer and Tesla's patents and challenged the DC premise. As a result, AC became the adopted method for transmitting and distributing power [6, 77].

However, with the development of switching devices, inverters, and DC-DC converters within the last 50 years, DC finally could be utilized effectively in a distribution network. Still, DC did not gain much attention until DC based renewable energy began to appear. This proposed an entirely new spin on the transmission and distribution system. First, transmission in DC became a hot topic with significant investment into the research of high voltage DC (HVDC). HVDC demonstrated compelling efficiency and maximum transfer capability while supplying stability to the distribution and generation networks. This led to other low voltage studies in DC. These are discussed in Chapter 2.

Therefore, a reevaluation of the current power infrastructure is paramount in determining more efficient avenues of applying renewable energies. Important aspects including efficiency, maximum transfer capability, distributed generation, and economics along with key requirements in evolving to a DC power system are crucial in assessing the gains of a DC distribution system.

1.2 Distributed Generation

Distributed generation is the arrangement of multiple generation sources within the distribution system instead of at a centralized location. The established distribution system is founded on a centralized theme: a utility transmits power from generation facilities to substations and substations reduce the voltage for transmission to buildings. This transmitted power condones sizable losses and extensive costs from transmission lines and transformers.

A distributed generation network can reduce energy transmission by applying energy sources in the more immediate neighborhood of the loads. Decreasing the transmission power not only conserves energy but enables a reduction in distribution line and power device rating. Additionally, distributed generation liberates the transmission lines to deliver more power to necessary loads without incorporating extra lines. Therefore, exercising fuel cells as a distributed source can reward utilities with significant energy and financial savings. Even so, the optimal placement and generation capacity of fuel cells as distributed generation sources must be investigated before designating proper placement within the distribution network. Poor allocation can conceivably result in unwanted losses or additional costs.

1.3 Fuel Cells

Fuel cells have been recognized as proficient distributed generation sources as a result of their scalability, freedom in location, and high efficiency. Fuel cells are deemed environmentally sound with little to no pollution. Nevertheless, applying fuel cell technology is contingent on overcoming some inherent obstacles [7].

Fuel cell technology is not a new science, but has origins as far back as the nineteenth century. In 1839, William Grove discovered that electrical energy was manufacturable through combining oxygen and hydrogen in a particular configuration [8]. Although Grove's experiments were primitive compared to today's fuel cell technology, the basic principle is still applicable.

The schematic shown in Figure 2.1 discloses a fundamental depiction of a fuel cell. The prominent components are the cathode, anode, and a bisecting membrane. At the anode, a catalyst separates the supplied hydrogen gas into electrons and positive hydrogen ions. The membrane permits the positive hydrogen ions to permeate from the anode to the cathode directly while rejecting the electrons to a provided electrical path. As the electrons and positive hydrogen ions reach the cathode, they recombine along with oxygen to produce water. The following basic reactions demonstrate the process [7-12]:

Anode side: $2H_2 \Rightarrow 4H^+ + 4e^-$

Cathode side: $O_2 + 4H^+ + 4e^- \Rightarrow 2H_2O$

Net reaction: $2H_2 + O_2 \Rightarrow 2H_2O$

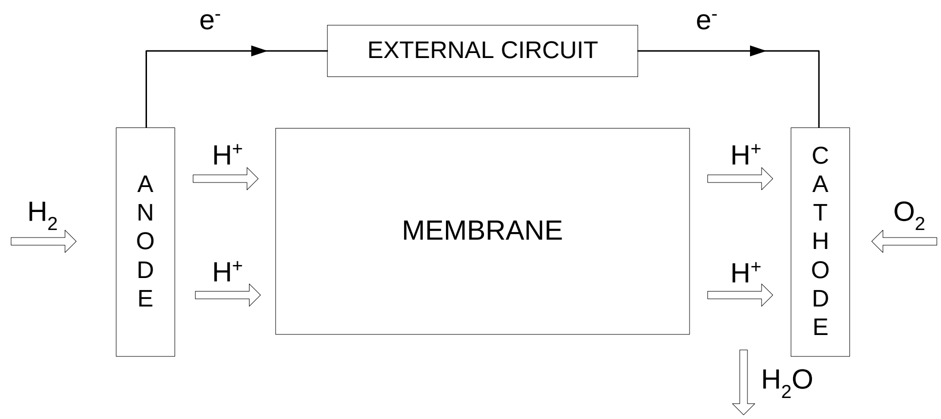


Figure 2.1 Basic fuel cell schematic.

Development of fuel cells for large power generation facilities can be decomposed into several steps. Rectangular or cylindrical tubes sculpt the fundamental components, the anode, cathode, and membrane and are responsible for the generation and recombination of electrons. These tubes are packaged together in series and parallel combinations to create a unit known as a fuel cell stack capable of producing between a few kilowatts to a hundred kilowatts. Large-scale power generation necessitates further consolidation with fuel cell stacks amassed into generation facilities capable of generating between sub-megawatt to megawatts [7-12].

A variety of competing designs for fuel cells have been fashioned. The following is a list of the fuel cell types:

- Alkaline Fuel Cells (AFC)
- Phosphoric Acid Fuel Cells (PAFC)
- Proton Exchange Membrane Fuel Cells (PEMFC)
- Molten Carbonate Fuel Cells (MCFC)
- Solid Oxide Fuel Cells (SOFC)

Classification of fuel cells has largely been founded on operational temperature. Fuel cells operating at temperatures below 250 ºC are recognized as low-temperature and include AFC, PAFC, and PEMFC. A crucial factor in the operation of this type of fuel cell is the availability of pure hydrogen. Fuel processors and reformers are often necessary to develop fuels such as natural gas, coal, and biomass into hydrogen reducing the overall efficiency. However, the high power density, quick startup, and low temperature make these fuel cells ideal for vehicle applications. Past and current work with these fuel cells have included [7-12]:

- Space vehicles such as Apollo.
- Commercial vehicles
- Combined heating and power generation (CHP)
- Small power plants (several were installed in Germany and have been under operation for over 40,000 hours)
- Portable power for electronics

High temperature fuel cells typically operate at temperatures exceeding 500 ºC and include MCFC and SOFC. Due to the higher temperature, these fuel cells can utilize different fuels without a reformer with reactions occurring more readily and efficiently then their low-temperature counterparts. This reduces the overall cost, since the catalyst implemented by the low-temperature fuel cells, platinum, is no longer necessary. Likewise, efficiency improvements can be made through cogeneration. Nevertheless, these fuel cells generally have slow startup times which are a deterrent for small-scale operation. Thus, high-temperature fuel cell applications have primarily focused on small to large stationary power plants, where the high efficiencies, automatic internal reforming, and co-generative capabilities outweigh the slow startup. Past applications of high temperature fuel cells include [7-12]:

- Department of Energy and FuelCell Energy built several MCFC sub-megawattt power plants in Europe that have provided 17 million kWh of power
- Siemens Westinghouse has developed and tested a 250kW SOFC hybrid system that has achieved 52% efficiency.

Although fuel cells are tremendously important with significant assets, fuel cells do suffer from some technical challenges including low output voltage that varies with age and current, reduced efficiency with output ripple current, slow response to a load step change, no overload capability, and no acceptance of reverse current. Still, these issues can be mostly resolved through PE devices [4, 7].

1.4 Chapter Summary

DG sources are a tremendous asset in reducing the burden on transmission, increasing the efficiency of the power system, and lowering costs. Fuel cells are one of the best choices for DG, since location restrictions are non-existent, power output is variable, and these devices have high efficiency. Presently, however, additional power electronic (PE) devices are necessary to convert the direct current (DC) rendered by fuel cells to alternating current (AC) for the distribution system reducing efficiency. A conceivable remedy for the losses associated with PEs is the metamorphosis of the distribution system to DC. Along with potentially increasing efficiency of the distribution system, DC could serve other benefits.

1.5 Outline

Application of fuel cells is contingent on efficiently supplying energy to the distribution system and ultimately to loads. This is hypothetically possible through a DC distribution system. This dissertation will focus on applying fuel cells to a modified DC distribution system.

Chapter 2 embarks with a literature survey of work conducted on DC distribution and fuel cells. Work relating efficiency, maximum power transfer, fault analysis, reliability, distributed generation placement, and economic analysis of DC distribution and fuel cells will be examined.

Chapter 3 revolves around a discussion of the differences in AC and DC systems and possible avenues for retrofitting. A review of fault interruption, converter topologies, and distribution lines will be conducted.

Chapter 4 embodies the power system software implemented in analysis, SKM. This is accompanied by an examination of the DC system equations and algorithms employed for system analysis along with algorithms for optimum deployment of fuel cells.

Chapter 5 covers the results of several simulations based on equations and the software discussed in Chapter 4. Results are examined for importance.

Chapter 6 wraps up this dissertation with an examination of the results in Chapter 5 and development of a conclusion on the future of a DC distribution system.

2 BACKGROUND

In the previous chapter, the discussion opened around applying alternative energy technologies, such as fuel cells, in the ORNL distribution network. Fuel cells in an AC distribution system require PE devices to convert the DC power generated to AC for distribution possibly resulting in significant reductions in efficiency and reliability while incurring more cost. Furthermore, any DC loads would again necessitate conversion of the power from AC to DC. For these reasons, a DC distribution system is proposed.

This chapter will examine previous studies related to DC distribution. Efficiency, cost, power transfer capability, reliability, and fault analysis of DC distribution systems in relation to their AC counterparts will be reviewed. This will be followed by an examination of work conducted concerning optimization algorithms for placement of distributed generation, where the primary focus of these algorithms is the reduction of system losses.

2.1 AC and DC Distribution Studies

A substantial number of studies with varying applications have investigated the merit of a DC distribution system. Remarkably, a compelling number of these studies have competing arguments. Numerous studies have suggested that DC distribution is a more viable solution with reduced losses and cost, higher reliability, and improved power transfer capability while others have alleged the complete opposite. In the following subsections, a review of DC studies for data centers, telecommunication, residential, commercial, distribution, and transmission is conducted.

2.1.1 *Data Centers*

Data centers store and transfer tremendous amounts of digital information. This information often includes cellular communications, the internet, and credit card transactions. Although customers heavily rely on non-interrupted access to this information, service is expected to be inexpensive. To boot, the energy consumption of these data centers is expected to be as much as 20% of the total cost [16]. Hence, viability of a data center often rests on the reliability, efficiency, and electrical energy cost of the data center. Two diverse approaches to modeling the differences in AC and DC for data centers systems are discussed [13, 14].

One analysis of a data center power system with five distinct models has been formulated and is shown in Figure 2.1 [13]. These models represent typical data distribution systems for (a) AC in American, (b) AC outside America, (c) a telecom DC power plant, (d) high voltage DC, and (e) a hybrid DC system (power system containing multiple voltages of DC). For AC systems, an uninterruptible power supply (UPS) provides continuous power to the information technology (IT) loads, whereas in DC, a DC plant (a DC power supply along with a battery) is implemented. With these models, efficiency, cost effectiveness, and reliability of AC and DC are compared.

In development of an efficiency analysis, variations in device operation (full and partial loading) are considered. Under full load, high voltage DC showed the most promise with slightly improved efficiency over high voltage AC as shown in Table 2.1. The high voltage systems have lower currents and thereby lower losses. However, high

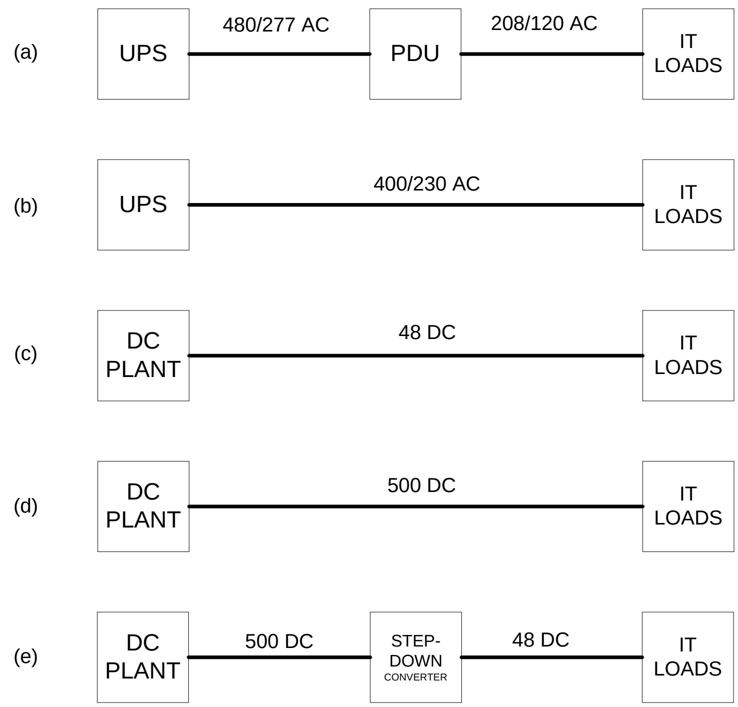


Figure 2.1 AC and DC systems for data centers [13].

voltage DC netted lower efficiency in relation to AC when the system is partially loaded. This is due to the efficiency curve of power electronic devices. This is discussed more in Chapter 3. Since data centers are typically oversized to furnish a safety margin, data centers tend to operate below full loading suggesting that high voltage AC is inherently more attractive [16].

UPS devices tend to cost as much as 10% to 30% more than a power rectifier/battery plant. Although this would suggest a higher premium for AC, these savings are anticipated to be offset by the wiring necessary for low voltage DC, as these conductors would need to be larger to carry the higher current. Furthermore, equipment

Table 2.1 Data center distribution efficiency results [13]

Power Type	System Under Full Load	System Under Half Load	System Under Quarter Load
AC System	76.4%	75.0%	71.5%
High Voltage AC System	77.3%	77.0%	75.4%
48V DC System	73.6%	72.5%	69.7%
High Voltage DC System	78.8%	77.3%	74.0%
Hybrid DC System	71.0%	66.9%	59.8%

for DC tends to be more expensive due to the maturity of AC, thereby giving AC a slight advantage.

While a decisive winner is present with efficiency and cost in this analysis, no definitive leader is present for reliability in this study. Similar reliability figures have been located for both UPS systems in AC and rectifier-bridge and battery combinations in DC. Configurations of these devices either in AC or DC distribution networks are likewise comparable, consequently, no meaningful difference could be found.

Nevertheless, these findings contradict a separate analysis with the models provided in

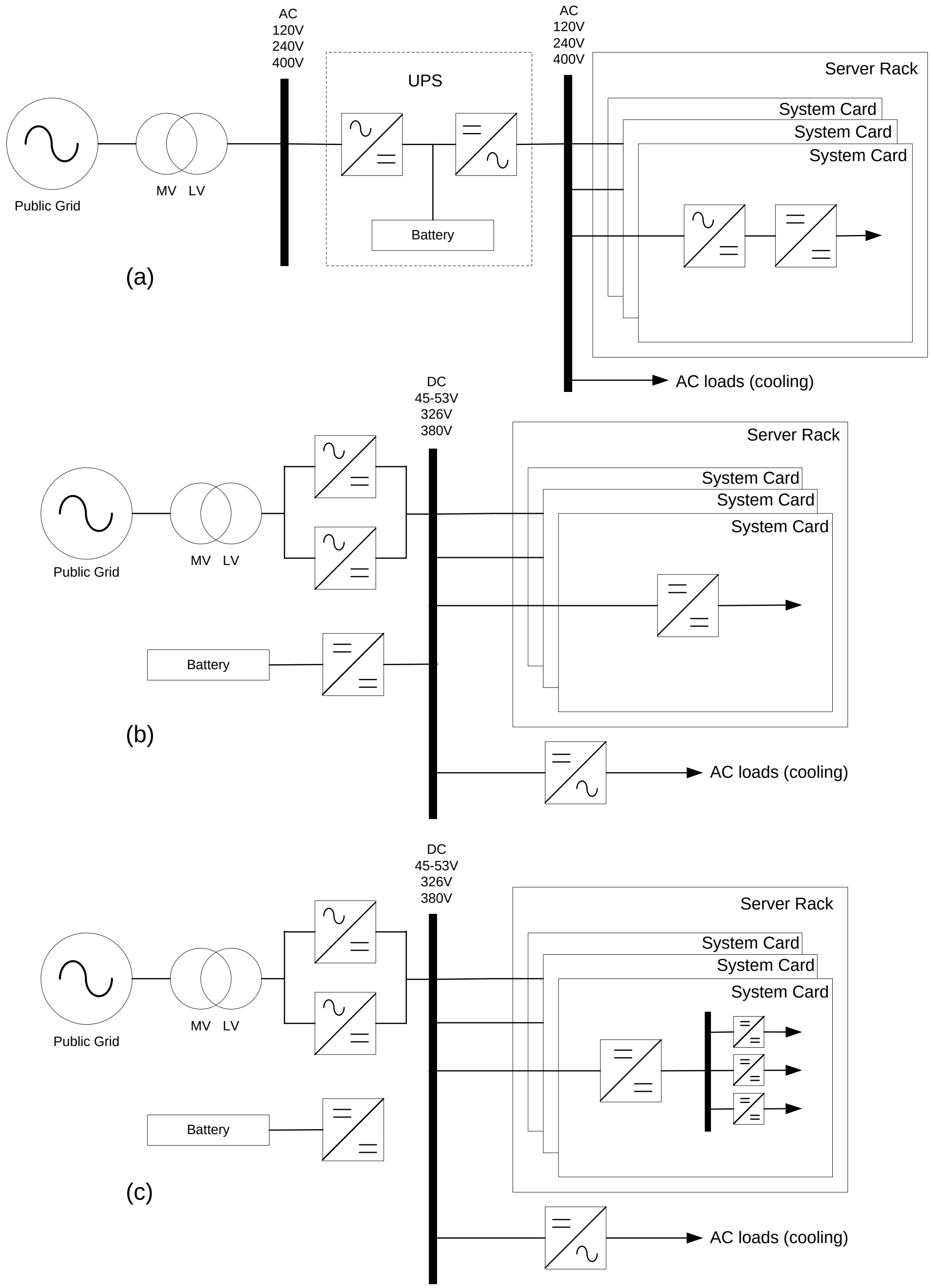


Figure 2.2 [14]. Three detailed power system models have been constructed to represent different data center systems: an (a) AC, (b) DC, and (c) DC system with an intermediate bus. The absence of reactive power, integration of distributed generation, and a reduction in the number of converters are reasoned to lead to notable benefits in DC. An intermediate DC bus system has been constructed to provide low DC voltage to the loads thereby eliminating the high currents on the main bus.

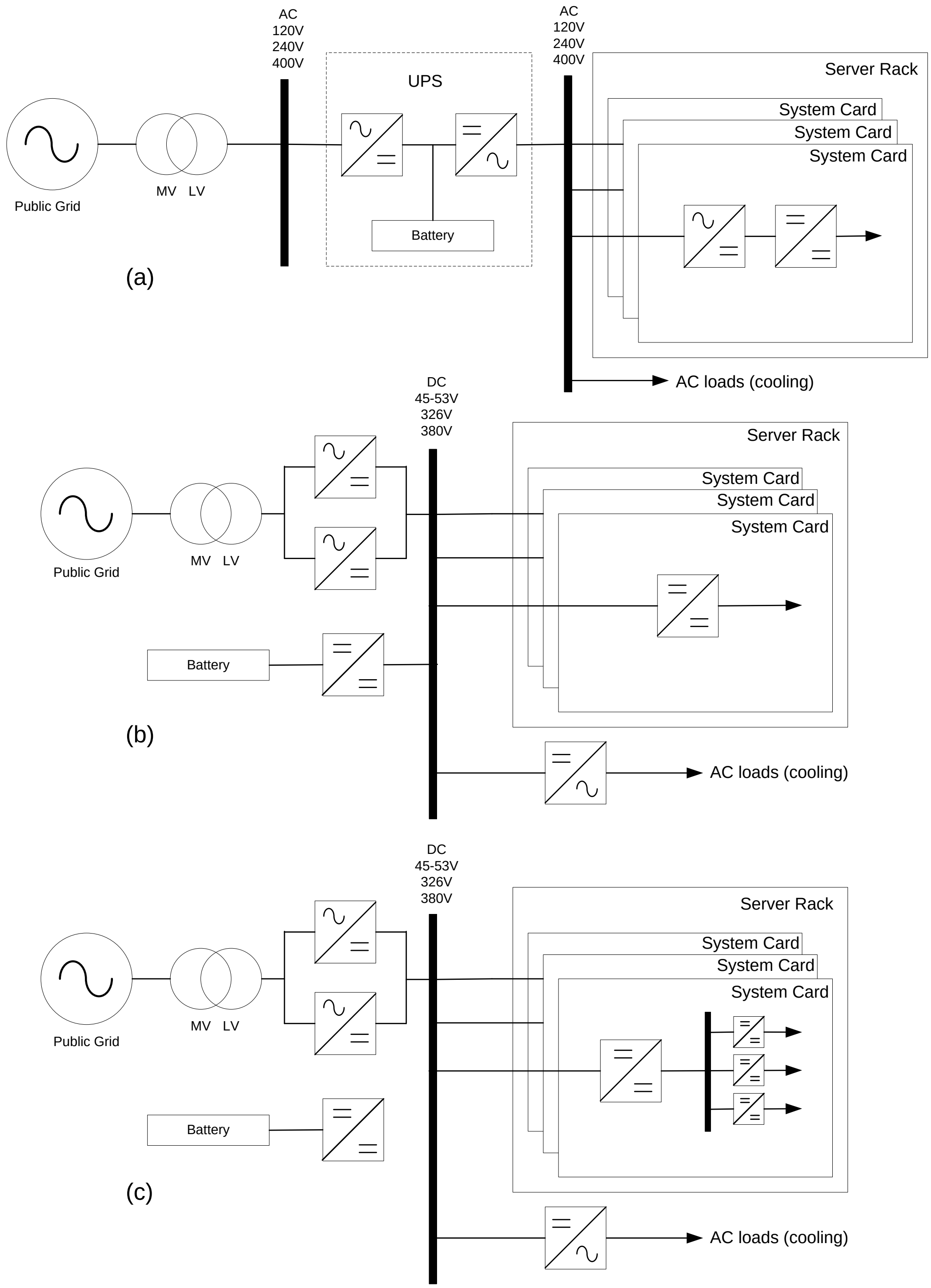


Figure 2.2 AC, DC, and DC with intermediate bus models for data centers [14].

Enhancement in efficiency can be induced through an examination of the typical losses of a server card and the elimination of a converter in the UPS. As shown in Figure 2.3, most of the losses in typical server cards arise from the ac-dc converter. Discarding this converter can save 131W of energy and result in an 8% savings for the overall data center system. Similarly, a gain of 9% is predicted in removing the converter in the UPS, producing a combined increase of 17% in savings. Additional savings are assumed with the elimination of reactive elements and the addition of DC renewables, but no calculations are performed.

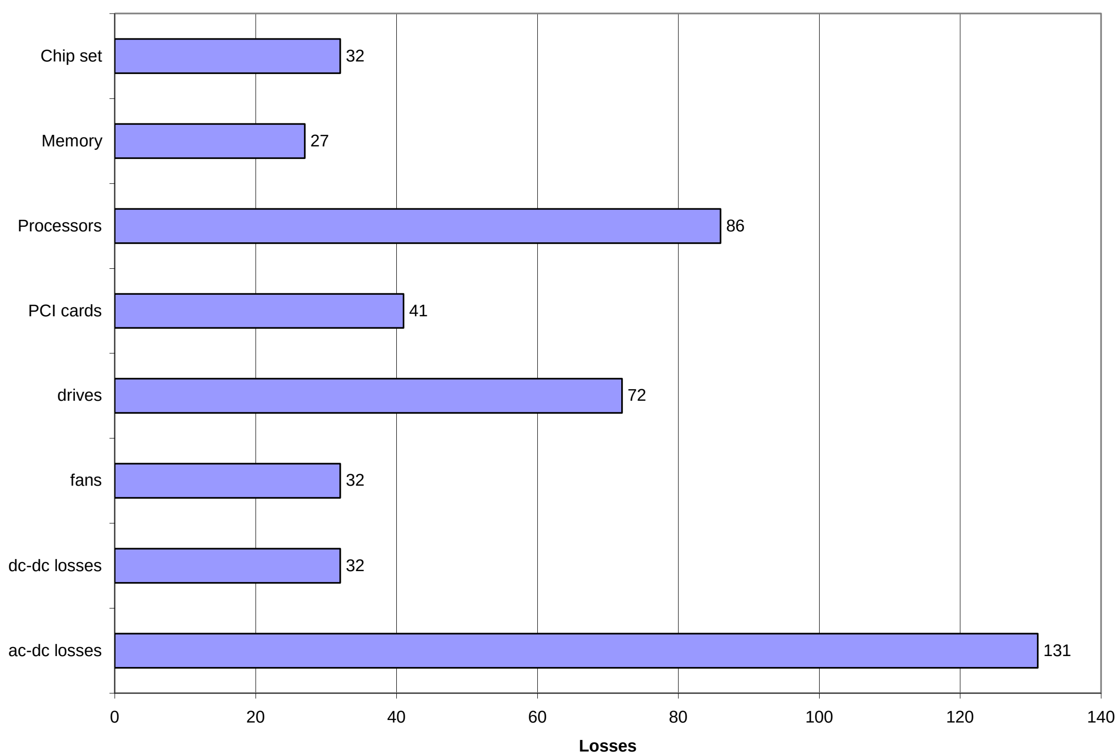


Figure 2.3 Typical server card losses in Watts [14].

Reliability improvements are founded on the reduction of converters as well and a comparison of the AC-DC and DC-DC converters. Power electronic converters have a low mean time between failures (MTBF) compared to other power system components. Hence, a decrease in the number of converters would improve MTBF. Moreover, AC-DC converters have worse MTBF in relation to DC-DC converters due to the implementation of more semiconductors.

2.1.2 Telecommunications

Similar to data centers, telecommunication networks transfer immense amounts of information. Customers depend on cheap availability of this information. Therefore, a telecommunications network should have a high reliability and efficiency, with a low cost [15].

An inspection of power system for telecommunications has been conducted with the models depicted in Figure 2.4[15]. For this investigation, efficiency and reliability are the chief concerns. Two independent systems have been analyzed:

(1) DC distribution with DC loads connected directly to the distribution system and AC loads fed by inverters

(2) AC distribution with UPS delivering power directly to the AC loads and indirectly to DC loads by means of a rectifier.

Simple calculations of pure AC and DC systems netted equivalent operational efficiencies of both systems, thus proposing that the power system should be chosen on

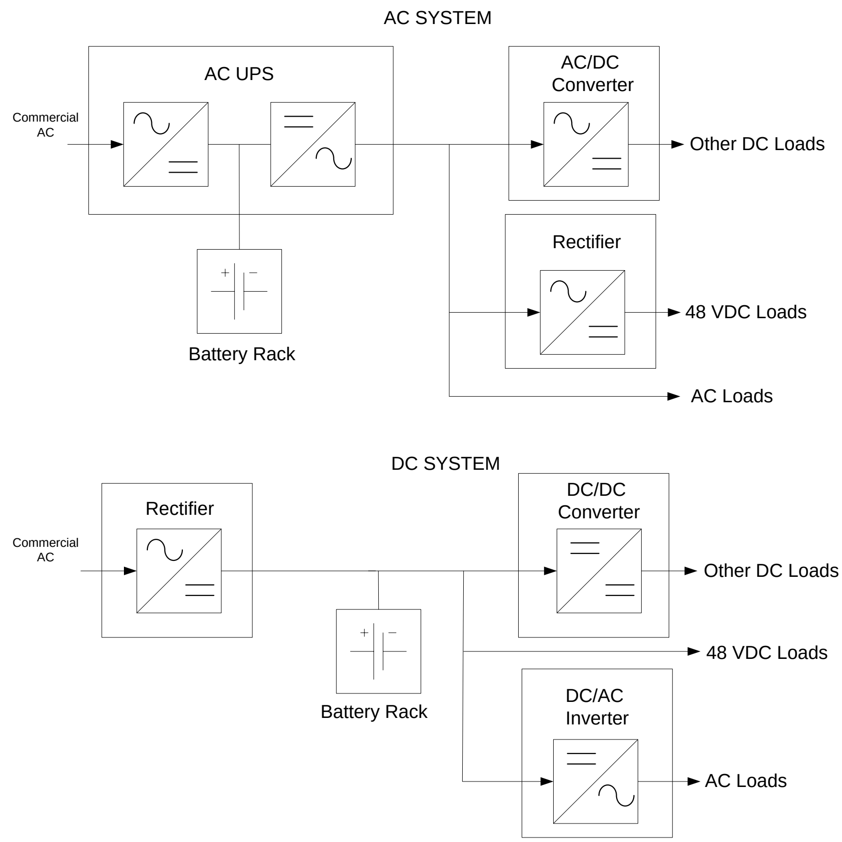


Figure 2.4 AC and DC power systems for telecommunications [15].

account of the proportion of loads. As typical internet hosting sites and server-based communication sites have 85% to 95% of the total electronic load as AC, AC would seem to have the advantage.

For the argument of reliability, several varying viewpoints exist. AC system has reliability issues in key areas from the excess electronics necessitated in the UPS, while DC has reliability quandaries from the MTBF of batteries.

2.1.3 Residential and Commercial Facilities

Residential and commercial facilities accommodate a variety of loads including, televisions, computers, air conditioners, refrigerators, motors and drives, and lighting to name a few. Analogous to data centers and telecommunication networks, residential and commercial facilities demand that cheap, non-interrupted power be delivered safely, efficiently, and with low harmonic content and high power factor [17].

Models for the comparison of AC and DC residential systems are shown in Figure 2.5[17]. Reduction of conversion devices, reactive power losses, and the elimination of standby losses are arguments for moving to a DC distribution system for residential application. These models focus on the energy efficiency, converter configurations, and safety of a small-scale DC distribution system for low voltage (600V). The developed model is based on an establishment with rough estimates of wire resistances, transformer and converter losses, and a loading profile. Although line conduction losses for DC are determined to be lower than AC, these losses only amounted to 0.3% of the useful power. To the contrary, converter losses are much more severe and system efficiency is highly dependent on their affect. Due to the high efficiency of transformers (usually exceeding97%) and the moderate efficiency of present DC-DC converters (generally around 95% at full load and 50% at 10% loading) an AC system is deemed more efficient.

In this investigation, several converter configurations have been examined. Merit

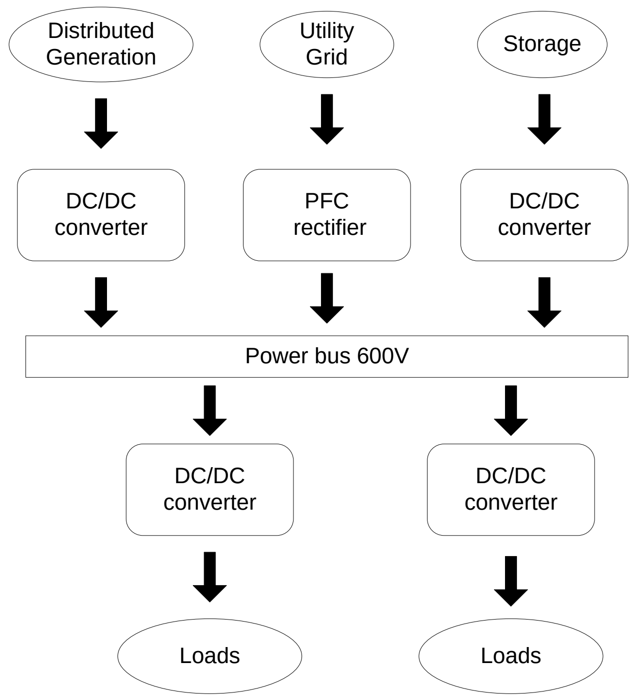


Figure 2.5 DC residential model [17].

has been given to a system that implements two parallel converters. Two parallel converters entitle the power system with multiple bus voltages while reducing the total rating of each converter. Moreover, short-circuit currents are predicted to be lower with this architecture.

In respect to DC interruption devices, interruption techniques are anticipated to be similar for AC and DC. The use of circuit breakers at each converter to interrupt any faults in DC is recommended. Although DC interruption devices are expected to undergo higher stresses, the necessary interruption capacity is foreseen to be much lower.

While the previous study analyzed the residential system as a whole, the proposed designs, illustrated in Figure 2.6 and Figure 2.7, represent the power distribution for homes of the future [18, 19]. The incorporation of electric vehicles, power quality issues with AC, computer systems, energy storage, and renewable energy are considered as chief motivations for implementing a DC distribution system within homes. Furthermore, a DC distribution system with energy storage alone would minimize generation fluctuations and outage time saving fuel and cost. The first design incorporates power factor correction, has energy storage capabilities, and local power generation to improve energy efficiency, cost, compatibility, modularity, and safety. The second composite utilizes a hybrid system with 230VAC for the large appliances and an AC/DC converter to supply DC power for lighting and most of the low level electronics. Calculations for performance were not performed for either scheme.

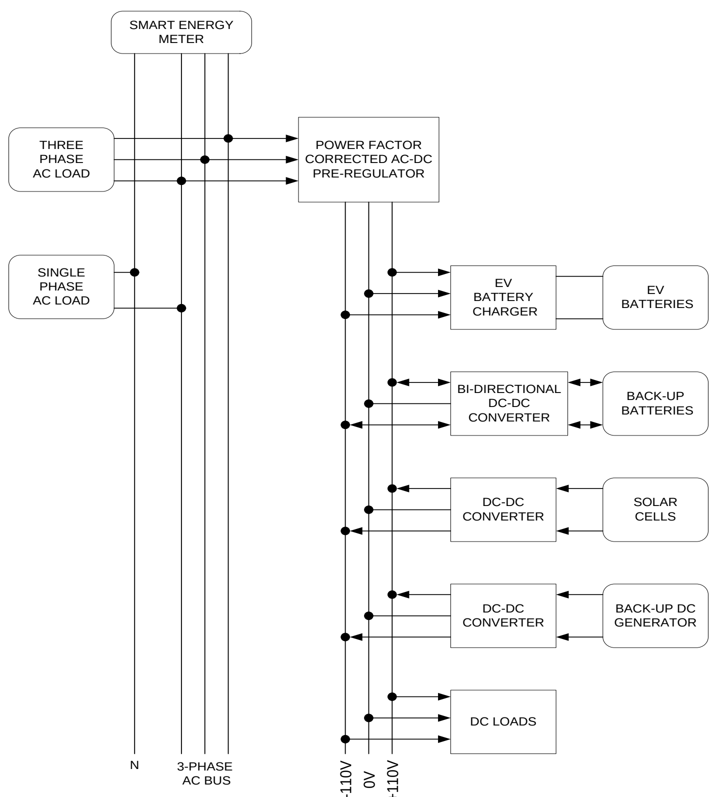


Figure 2.6 Power distribution system for future homes [18].

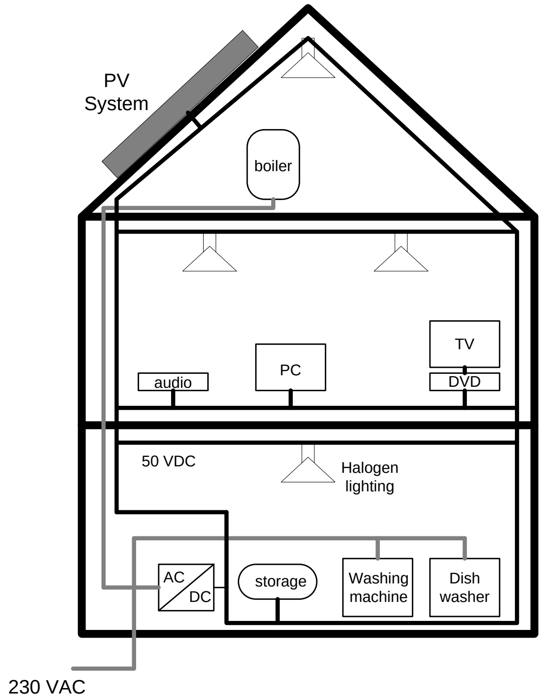


Figure 2.7 Future home distribution system [19].

A DC distribution system for a thirty-story building and school have also been investigated [20]. A schematic of the layout is provided in Figure 2.8. Justification of DC distribution comes from trends towards an increased number of DC loads such as computers, network equipment, and light emitting diode (LED) technologies and recent advances in air conditioning technologies that incorporate inverter driven air-conditioners.

This proposed configuration incorporates both AC and DC distribution. AC loads are supplied by a connection to the AC grid, whereas DC loads are either supplied by renewables or the AC grid through converters. In the model, conduction losses have been calculated separately for three portions of the distribution system, main circuit, sub-main, and the final circuit. The solutions of each have been resolved into a 3% gain in moving

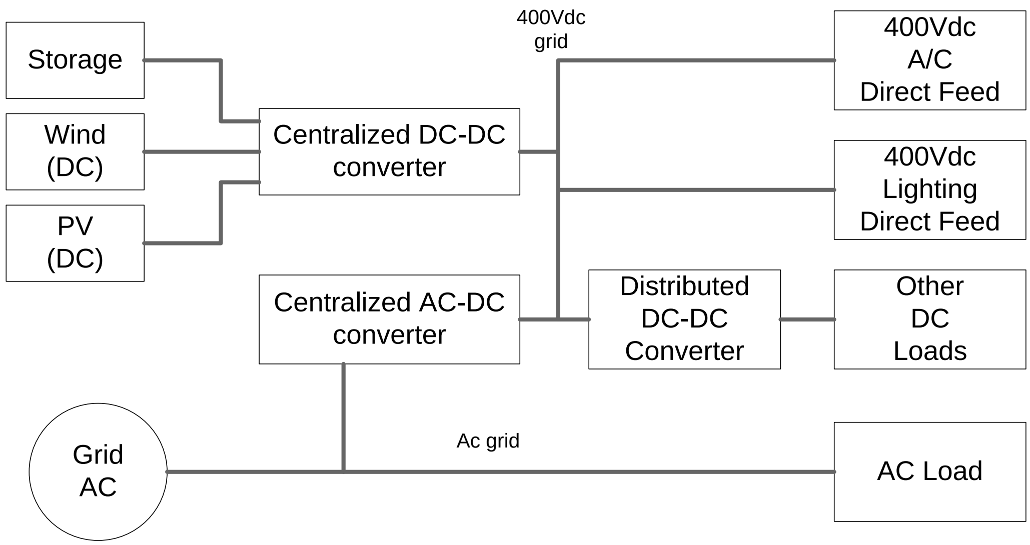


Figure 2.8 Schematic of proposed distribution system for thirty-story building and school [20].

to DC distribution system for DC loads. However, when converter efficiency is examined, an overall efficiency increase of 16% is found in moving to DC. Further benefits with DC distribution are predicted for cost, reliability, and power quality through the elimination of converters and simplification of the distribution system as a whole.

The feasibility of a DC distribution system in a commercial facility has likewise been examined [21]. As with other assessments, the primary goal is to eliminate the excessive amount of converters to increase the efficiency, cost, and reliability of the system. In this study, a portion of the Department of Electric Power Engineering at Chalmers University of Technology in Sweden is modeled. The model is comprised of thirty-six typical office loads such as computers, printers, fax and copy machines, refrigerators, cookers, exhaust fan, dishwasher, coffee machine, microwave oven, lighting, and water boiler. A single-line diagram of the model is shown in Figure 2.9. The

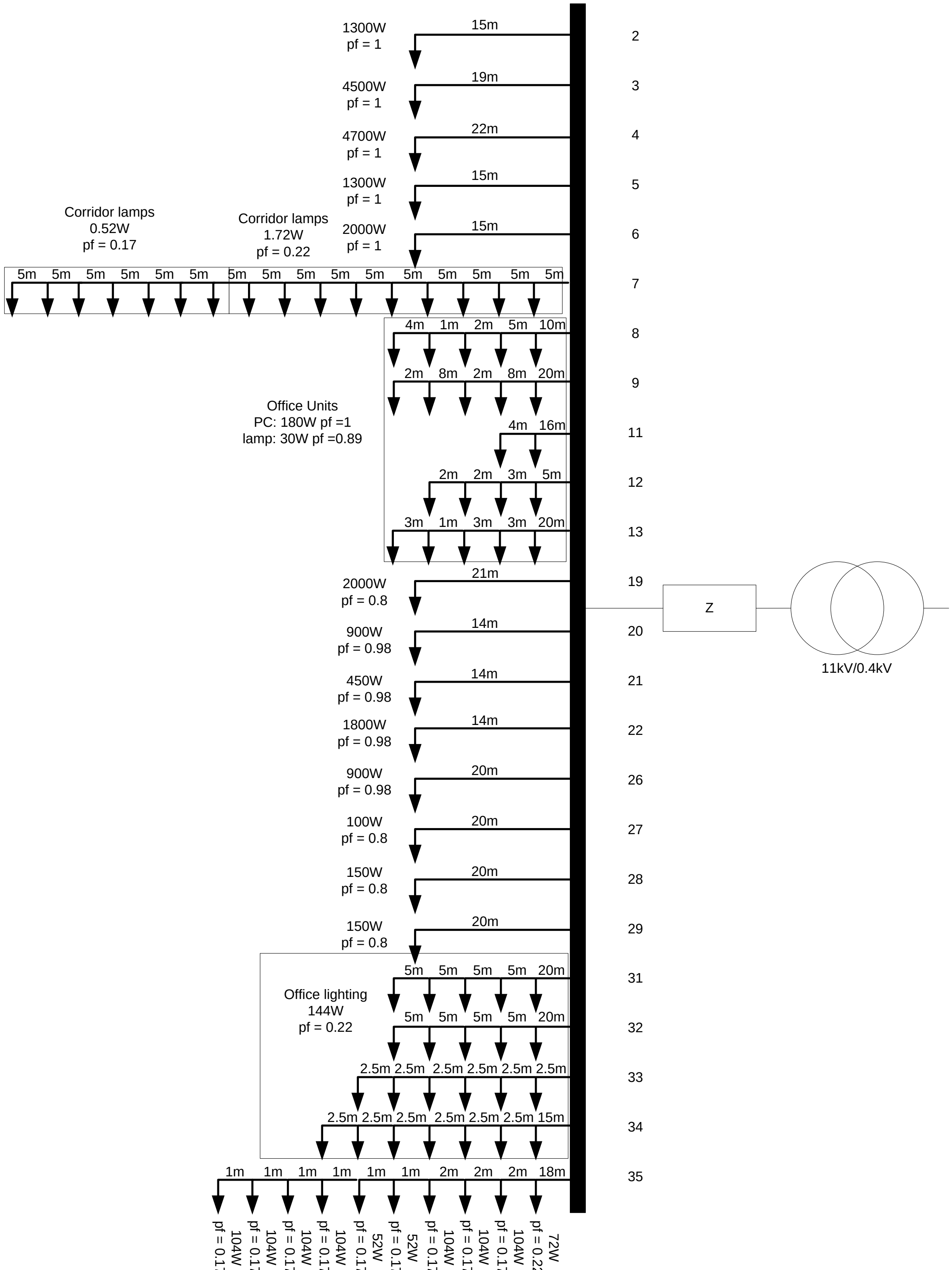


Figure 2.9 Calmers University of Technology loads [21].

power consumption of the loads and power factor come from long-term measurements of the voltage and currents.

The existing AC distribution system for Chalmers is based on 400V, while the DC system voltages for the model were 48V, 120V, 230V, and 326V. The DC voltage levels were chosen based on existing DC device voltage ratings. The model revealed that 48VDC and 120VDC are not acceptable voltages since a maximum voltage drop of 5% is reached in the distribution lines and the current rating of the cables are exceeded. For an economic analysis, a review of rectifier prices and operational costs has been performed. The final tabulation of efficiency and cost reveals that 326VDC is the optimum choice for DC distribution. Nonetheless, a quick calculation of the gains in not utilizing a UPS for AC, demonstrated efficiency and cost benefits with DC.

2.1.4 Distribution

The distribution of electrical energy accounts for 75% of the losses within the electrical system and 90% of the faults. As if this were not enough of a reason to evaluate the distribution system, consumers and industrial users mandate that inexpensive electricity be delivered uninterrupted. This ensures that efficiency, reliability, and cost of the distribution system remain paramount [22, 23].

The efficiency of low and medium voltage DC networks has been explored [23]. Elimination of standby losses and a reduction in transmission losses and the number of converters are exemplary incentives for a DC distribution. As displayed in

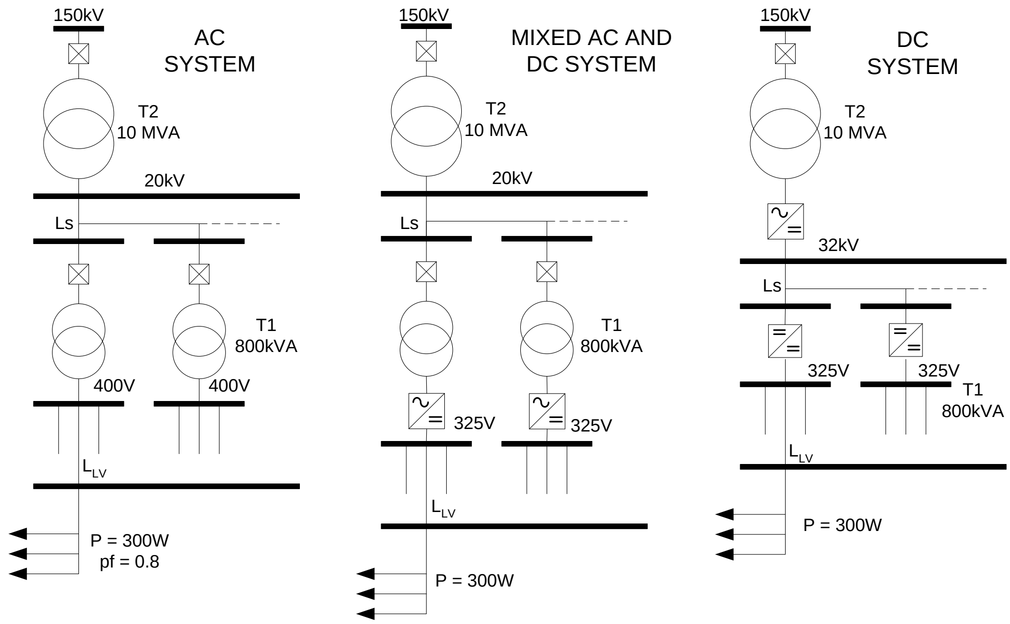


Figure 2.10, three envisioned systems have been developed: pure AC, mixed ac and dc, and solely DC. Cable parameters are founded on approximations of the radius of the expected cables. Transformer losses are established on efficiency while voltage source converters (VSC) in DC have been modeled using conduction and switching loss equations. For added effect, the switching frequency and resistance of the semiconductors in the model of the VSC have been varied.

In the study, the pure AC system maintained efficiencies between 97.3% and 96.4% owing to the high efficiency of the transformer. Results of the mixed AC and DC system were not as appealing and are found to be much lower. This is primarily due to the utilization of both a transformer and a VSC for the conversion of AC to DC. For DC, a unique configuration of the cables is presented to seemingly double the voltage thereby enhancing transmission efficiency. If the same cables employed for AC are utilized with dc voltage, a positive, negative, and neutral configuration could be implemented

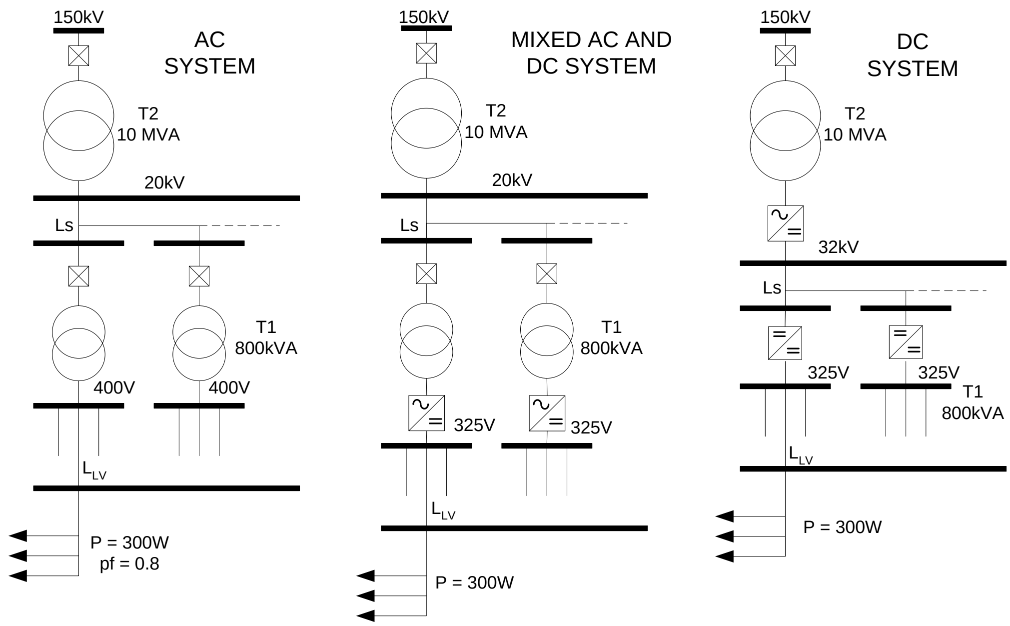


Figure 2.10 LV and MV distribution systems [23].

permitting voltage to be doubled without affecting the cables. Although the pure DC system had better efficiency compared to the mixed AC and DC system, a pure DC system still had more losses than a pure AC system.

2.1.5 Transmission

Since generation facilities tend to be located far from loads, transmission of electrical energy efficiently is vital. As with the previous cases, customers also demand power delivery to be inexpensive and reliable. Hence, cost, efficiency, and reliability are the three primary concerns in transmission of power. Three separate analyses are presented for comparisons of high voltage alternating current (HVAC) and high voltage direct current (HVDC) transmission.

One analysis focuses on a basic overview of HVDC [24]. In this examination, HVDC presents reduced cost, greater transmission capacity, and lower losses compared to HVAC. In obtaining a cost comparison, a cost structure is implemented that separates the necessary components for an HVDC system into cost percentages of the entire system. Vital components of an HVDC system, thyristors and IGBTs, converter transformers, smoothing reactor, and harmonic filter are critiqued. This structure reveals that filters, capacitors, and converters tend to make up a large percentage of the cost of the system. Hence, although transmission line costs are considered to be lower for HVDC, the stations located at each end of the transmission line require additional converters and filtering devices adding significant cost to the system.

Most of the losses in a transmission system are deemed to be a result of conduction losses and not the converter station. Since only 0.6% of the system losses have been established to arise from converter stations, calculations of system losses have been restricted to line losses. The calculations are based on equations relating the current density of a 25mm diameter conductor and an existing three-phase double circuit AC line. The double circuit AC system is assumed to have been converted to a three circuit bipolar DC system. The equations for power transmission are as follows:

$$P_{ac} = 6E_p I_L \tag{2.1}$$

$$P_{dc} = 6V_d I_d \tag{2.2}$$

Based on the calculations, comparisons of AC and DC are presented on Table 2.2. As shown, significant gains can be achieved with HVDC in terms of efficiency and maximum power transfer.

Another study has examined the differences of voltage source converter (VSC) driven HVDC and HVAC interconnections for a large offshore wind farm [25]. New power factor restrictions, reliability, and security of the power system have motivated an examination of moving to a VSC run HVDC network. A model of 184MW generation system consisting of 80, 2.3MW wind turbines has been developed [26]. These turbines are based on a fixed speed control with active stall regulation. The HVDC and HVAC models are shown in Figure 2.11. In the HVAC system, a static var compensator (SVC) is utilized to provide reactive power compensation.

Since power factor restrictions, reliability, and security are the main focus, the fault analysis has been deemed to be the most concerning. Therefore, two independent

Table 2.2 AC and DC maximum power transmission[24].

AC

Voltage (kV)	0.7 A/mm^2		1.0 A/mm^2		1.4 A/mm^2	
	P(MW)	Joule %*	P(MW)	Joule % *	P(MW)	Joule %*
33	26	11	37	16.1	52	22.6
132	130	3.5	180	4.9	262	7.1
* Represents a loss percentage in respect to the power transmitted per 10 km.						

DC

Voltage (kV)	0.7 A/mm^2		1.0 A/mm^2		1.4 A/mm^2	
	P(MW)	Joule %*	P(MW)	Joule *	P(MW)	Joule *
66	89	3.8	127	5.4	178	7.6
264	440	1.2	636	1.7	890	2.4
* Represents a loss percentage in respect to the power transmitted per 10km.						

faults have been simulated: one lasting 100ms and a second conducted for 625ms. Both systems survived the 100ms fault, returning to prefault voltage levels within .5s for HVDC and 4s for HVAC. The 625ms fault, however, met with different results. While the VSC HVDC system is able to return to prefault conditions within 2.5s, the HVAC interconnection became unstable. This is blamed on the SVC. The reactive power compensation created after the fault by the SVC forces the wind turbine to accelerate past the point of stability. Hence, HVDC is concluded to be a more reliable and secure method of power transmission.

A third study examines HVDC for interconnection of two large AC networks [27]. The original motivation for this study concentrated on foreseen stability

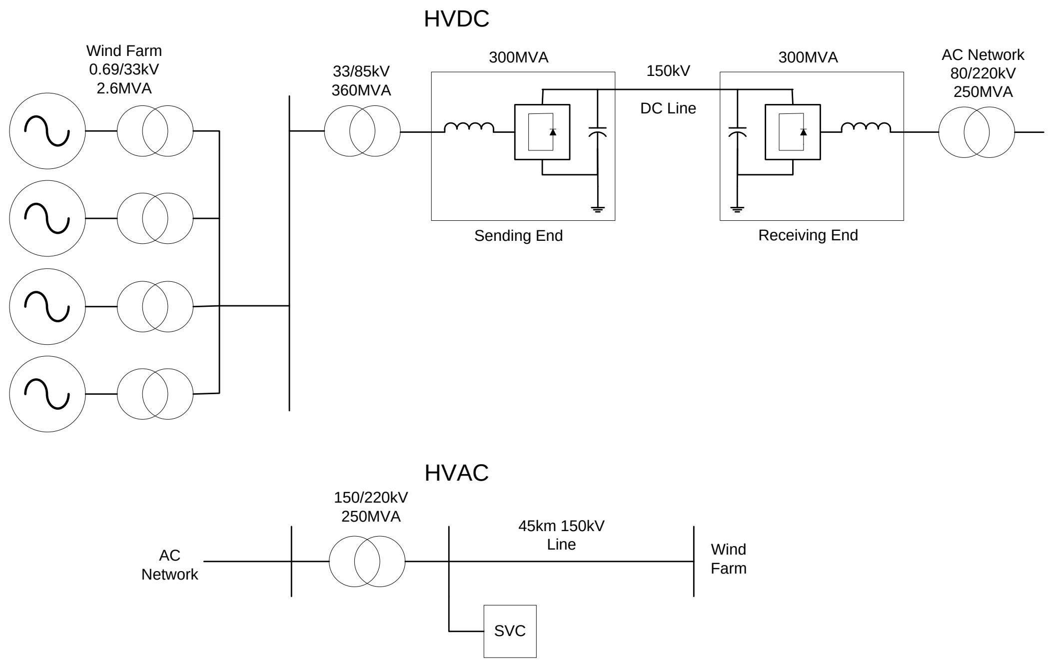


Figure 2.11 HVDC and HVAC transmission models for wind farm [25].

enhancement and declines in losses. Stability enhancement is anticipated since HVDC systems neither transmit nor source short circuit current to the interconnected AC systems while the award of efficiency derives from the delivery of power from less expensive generational facilities. However, both a traditional HVDC and a VSC driven HVDC system have been found to decrease voltage stability and transient stability of the surrounding AC system while having more losses.

In the AC system, the traditional HVDC system appears as a purely real generation source thereby generating no reactive power. This leads to poor power factors and voltage instability in the interconnected AC network that demand reactive power. Transient instability, on the other hand, arises with faults. Although the AC system automatically reroutes power after interruption of a fault, the HVDC system does not have this capability and instead places a significant burden on the neighboring AC lines. To prove this reasoning, a correlation of transient instability and voltage instability to the AC resonance frequency has been developed [28]. By examining the resonance frequency, HVDC has been shown to cause instability in the AC lines.

A loss analysis established through available industry information on converters and engineering estimates of line characteristics leads to Table 2.3. Although HVDC line losses are significantly lower than AC, HVDC conversion losses severely exceed those of AC resulting in the AC system being more efficient overall.

2.1.6 Other Studies

Due to the simplicity and conservation of space DC provides, DC distribution has also been implemented in a number of other studies and systems. Transportation systems such as trains, automobiles, ships, and airplanes have all been targeted for DC distribution systems as a result of the colossal number of electronic loads. Moreover, stability, safety, and reliability as well as energy storage have been key to promoting DC in these areas [29-32].

Table 2.3 Approximate losses for example transmission systems [27].

	Conversion Losses	Line Losses	Total Losses
AC	0%	1.2%	1.2%
Conventional HVDC	1.4%	0.5%	1.9%
VSC HVDC	5%	1.5%	6.5%

2.2 Optimum Location of Distributed Generation

A crucial feature for the acceptance of DC is distributed generation. Equally imperative is the optimized allocation of these generation sources. Improper placement of a generation source within the distribution network can lead to significant losses. Therefore, it is imperative that the proper location for a distributed generation source is found. The following subsections examine the varying techniques proposed in finding proper DG placement.

2.2.1 Zero-Point-Analysis

One analysis technique for finding the optimized location for DG creates a point in the feeder at which no power flows and is therefore provided the name "zero point analysis" [33]. This approach is restricted to radial distribution networks, where power is designed to flow from a single source directly to the loads and should only be considered as a "rule-of-thumb" for modeling DG networks. In this method, two categories distinguish DG placement: DG output is less than the downstream loads and DG output is more. When the DG output is less, the DG unit reduces the power flow on all the equipment between the DG and the main substation as shown in Figure 2.12. This allows for components to have reduced ratings. However, when the DG output is more, the power will reverse direction between the main substation and DG, creating a zero point.

Although the total power flow is lower, insinuating lower losses, the alteration in direction of power flow necessitates an investigation into the protection devices and voltage dynamics of the system. Nevertheless, a "2/3" rule is already implemented in

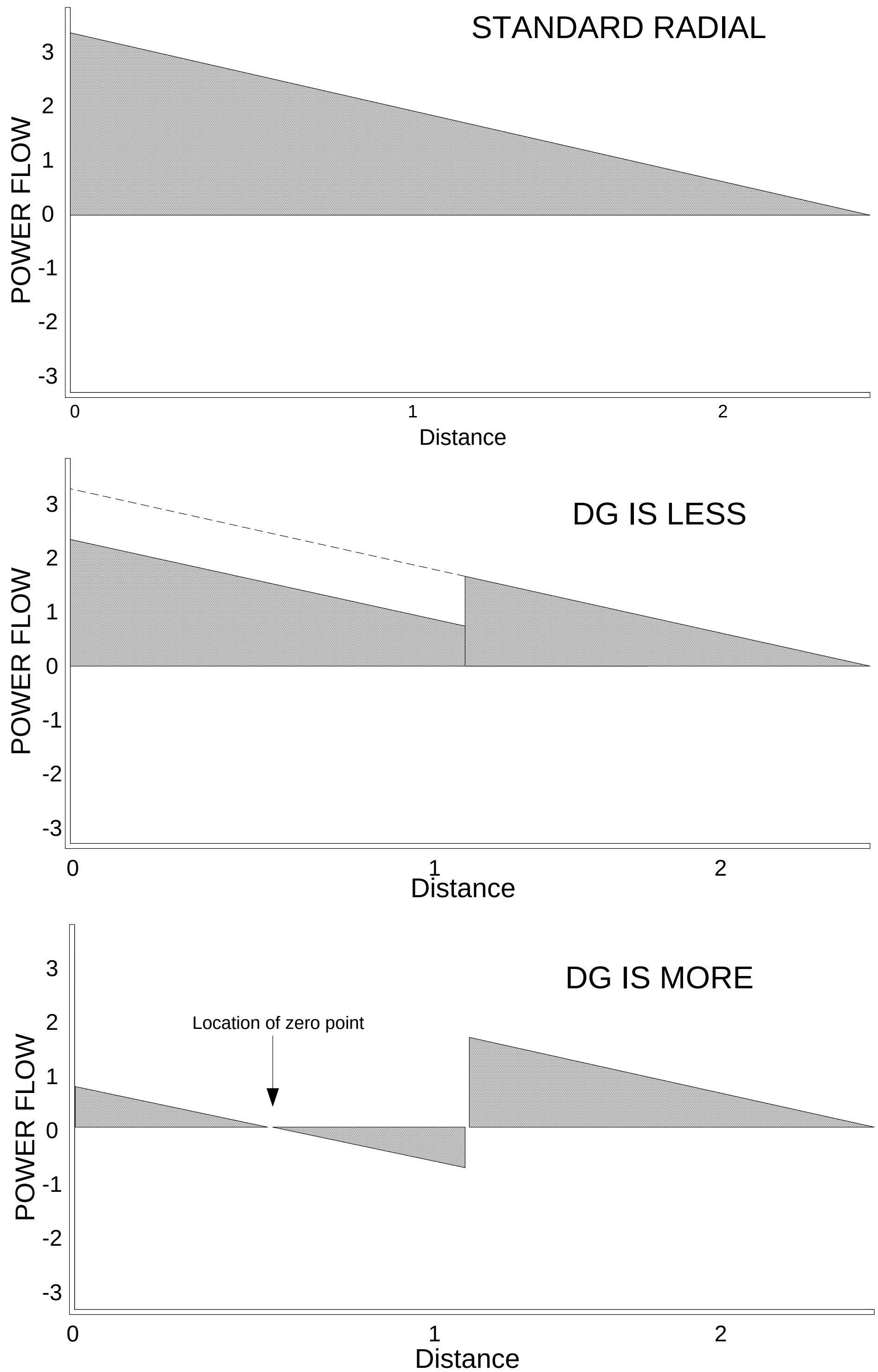


Figure 2.12 Zero point placement of DG [33].

capacitor placement in power systems. The “2/3” rule works by placing a DG unit that produces more than the downstream load, “2/3” of the distance down the feeder thereby instigating a zero point (power flow is zero) between the main substation and DG unit. Still, although zero point analysis is a convenient method for determining a reduced loss location, the method is only an approximation and can lead to error.

2.2.2 *Iterative Classification Approach*

Another approach for optimum DG unit placement for reduced losses is an iterative technique that utilizes power system software [34]. This technique relies on relatively accurate system information and classifies system buses based on generation placement.

The first step of this technique is to conduct a base case analysis of the system through load flow analysis. In respect to the locations with the highest losses, a set of primary locations for generation placement is established. Using these locations, generation units of a standard size are inserted and losses are recalculated. From these findings, a ranking system or classification is developed for the buses based on the reduction of system losses. According to the ranking, generation units are applied until losses either increase or desired amount of generation has been reached.

2.2.3 *Analytical Approach*

One analytical approach for determining the optimum placement of a DG in an AC radial feeder is conducted through an examination of three basic systems: uniformly distributed load, centrally distributed load, and increasingly distributed load [34, 35]. The basic approach assumes that the loads are distributed along the feeder with the phasor current I_d so that the current at point x along the feeder is:

$$I(x) = \int_0^x I_d(x)dx \tag{2.3}$$

The associated losses along the feeder are then

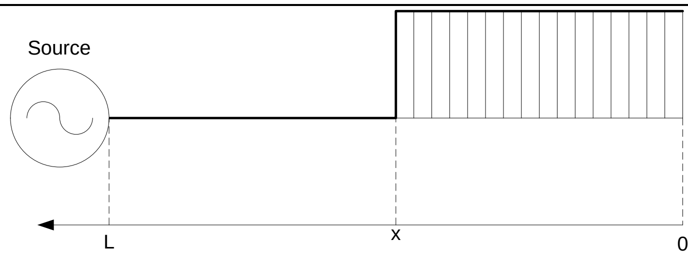
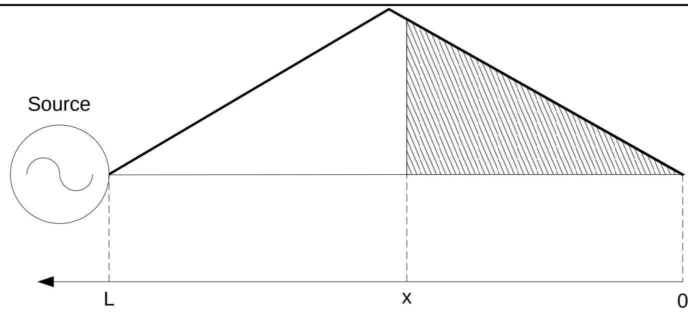
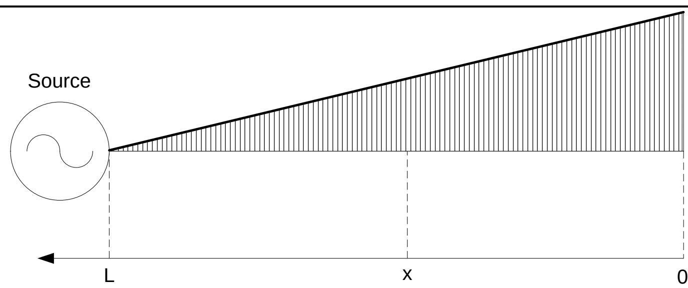
$$P_{loss}(x_0) = \int_0^{x_0} \left(\left| \int_0^x I_d(x)dx \right| \right)^2 Rdx + \int_{x_0}^{l} \left(\left| \int_0^x I_d(x)dx - I_{DG} \right| \right)^2 Rdx \tag{2.4}$$

where x_0 is the location on the feeder of the DG unit, I_{DG} is the injected DG current, and R is the line resistance with units of Ω/km. To find the optimum location of DG, the power loss equation is differentiated, set equal to zero to find the minimum, and solved for x_0. Several example systems and their respective optimal placements are shown in Table 2.4.

2.2.4 Optimal Control Methodology

Another approach implements optimal control (OC) techniques [36]. Optimal control is based on the idea of minimizing a constrained problem through integration. Table 2.5 demonstrates the control variables, state variables, and minimization equation for the OC problem. In this case, the power supplied by the DG units belongs to the control variables, and the voltage magnitude and angle for these buses correspond to the state variables. Bus 1 is the exception as this bus is considered to be the bus with the main supply of power. This bus has a constant voltage magnitude and angle with power

Table 2.4 Analytical approach examples [35].

Example System	Optimum Location
 Uniformly distributed load	$\frac{L}{2}$
 Centrally distributed load	$\frac{L}{2}$
 Increasingly distributed load	$\left(1-\frac{\sqrt{2}}{2}\right)L$

requirements determined by the system. This is necessary for the system calculations to converge. The goal of this optimization is to minimize the amount of generation. Minimization of generation implies a minimization in losses.

2.2.5 Particle Swarm Optimization

A methodology for optimization of dispersed energy through simulation of social behavior of living creatures is known as Particle Swarm Optimization (PSO) [37]. PSO interprets the gathering and movement of life such as a flock of birds or a school of fish. Essentially each particle in a swarm within an n-dimensional space is represented by a position and velocity vector. As the particle moves within this n-dimensional space, the best locations for each individual particle and the whole overall swarm are stored. Each new position is determined by a random multiplier, the best position located for each particle, and the swarm. The following equations demonstrate this process:

$$v^{t}{}_{ij} = v^{t-1}{}_{ij} + c_1 r_1 (p^{t-1}{}_{ij} - x^{t-1}{}_{ij}) + c_2 r_2 (G^{t-1}{}_{ij} - x^{t-1}{}_{ij}) \tag{2.5}$$

$$x^{t}{}_{ij} = x^{t-1}{}_{ij} + v^{t}{}_{ij} \tag{2.6}$$

Table 2.5 Optimal control equations [36]

Control Variables	$U = P_2, P_3, \cdots P_n$
State Variables	$x = P_1, \delta_2, \delta_3, \cdots \delta_n, V_2, V_3, \cdots V_n$
Problem	$\min f = \sum_{i=1}^{n} P_i$ $subject\,to\,g = 0$

where v represents the velocity, x is the position, c is an acceleration constant, r is the random variable, p is the optimum position based on the individual particle, and G is the optimum position of the particle in respect to the swarm. This process is repeated until a specified number of iterations have been reached. For DG placement, three variables are implemented instead of the velocity and position: bus number, generated power, and bus voltage.

2.2.6 Tabu Search

Unlike the random movement of PSO, Tabu Search (TS) initiates a search of neighboring solutions to find the optimum locations for DG [38]. Each solution within proximity of the previous solution is analyzed for comparison. If the neighboring solution is more optimum, the current solution is replaced with the neighboring solution and placed on the "tabu list." Any solutions placed on the "tabu list" are no longer candidates for examination. This procedure is continued until the solution reaches an optimum or the number of iterations has been reached.

For DG placement, the neighborhood solutions refer to the addition or removal of DG units from any candidate bus that is not already on the "tabu list." The candidate buses are chosen based on system limitations. A maximum number of DG installations and total capacity are required to formulate the problem.

2.3 Chapter Summary

From the aforementioned studies, the assets of DC distribution are controversial. Authors of these investigations proposed varying efficiency, cost, maximum transfer capability, and reliability. This is primarily due to the assumptions, applications, and models deviations. Diversified converter efficiency numbers, component costs, and reliability quotes led to many of the competing views. Furthermore, DC distribution could be an intermittent form of energy transfer for DC sources to DC loads. This fact is largely ignored by many of the authors. Therefore, an examination of different converter efficiencies, voltages, and system types is important in determining a fair comparison.

As optimization of DG placement is concerned, a significant number of methodologies have been presented. Nevertheless, these algorithms are generally too complex or overly simplified to find the best location. The zero point and iterative classification approach can find moderately fair locations for DG, but do not generally find the best. The analytical approach and OC methods are much too complicated to be applied to extremely large distribution systems. PSO and TS methods can find local optimums efficiently, but may not be able to find global optimums for an entire distribution system. In chapter 4, the genetic algorithm is discussed as the methodology for finding the optimum placement of DG in DC distributed systems.

In the next chapter, an examination of the fundamental differences in AC and DC distribution along with possible retrofitting is conducted. Close attention is focused on fault interruption, converter technologies, and distribution lines.

3 REVIEW OF FAULT INTERRUPTION TECHNOLOGIES, CONVERTER TOPOLOGIES, AND DISTRIBUTION LINES

In this chapter, a discussion of the differences in AC and DC distribution and possible methods for retrofitting with fuel cells is presented. Although there are a significant number of technical differences, three primary differences in AC and DC system became the focus. These include: fault interruption, power conversion devices, and transmission of power.

3.1 Fault Interruption

One obstacle faced with converting an AC system to a DC system is fault interruption. Fundamentally, the development of AC and DC faults is similar; both can have line to ground faults and line-to-line faults, but the fault interruption techniques of AC and DC systems do have contrast. To better illustrate, consider the basic circuit of Figure 3.1. In this circuit, E represents the potential voltage of the supply, R and L the value of the distribution line resistance and inductance respectively, and ea the voltage drop across the circuit protection device. When an electrical short is induced, as in this example circuit, the load is isolated and there is the appearance of a new load: the distribution line inductance and resistance and the voltage drop across the circuit protection device [39, 40].

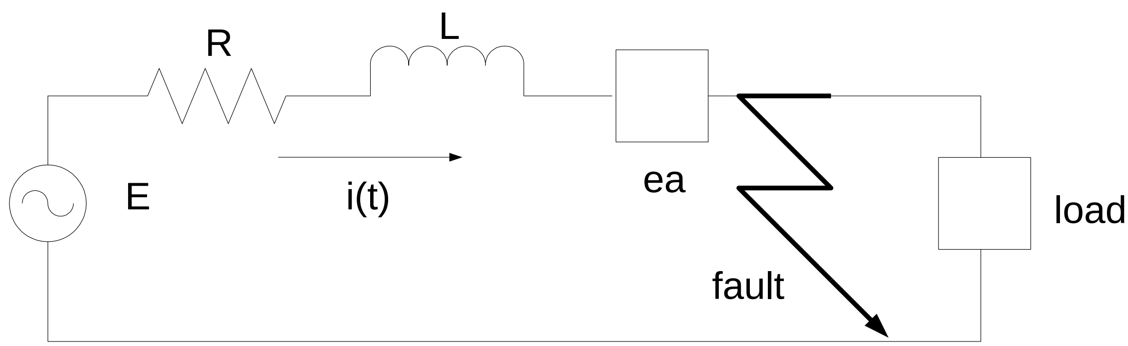


Figure 3.1 Basic short circuit with protection device [39].

By definition, a circuit fault is interrupted when the current passing through the circuit is zero. To reach zero current, the current must decrease, or a negative *di/dt* must be obtained.

If the protection device has been activated and an open circuit has been created, the following equation can be constructed using Kirchhoff's Voltage Law (KVL).

$$E = L\frac{di}{dt} + Ri + ea \tag{3.1}$$

This equation can be rearranged into the following form.

$$\frac{di}{dt} = \frac{1}{L}\left(E - Ri - ea\right) \tag{3.2}$$

From the above equation, a negative *di/dt* is only reachable if *ea* exceeds *E – Ri* or if the supply voltage E becomes negative. For AC systems this is easily achievable since *E* is alternating and will decrease to zero within ½ cycles, turning *E - Ri* completely negative and ultimately *di/dt* negative. However, this is not true for a DC system. Although during the initial onset of the fault E is equal to *Ri* creating a negative *di/dt*, the decreasing current leads to the growth of the *E-iR* term. If *ea* does not continue to exceed *E-iR*, than di/dt will either become zero or positive and current will flow indefinitely unless a failure in the circuit should occur either in the line creating an open circuit or in the supply voltage.

Two basic methodologies have been applied for fault interruption in DC systems: forcing a zero point in the current and increasing the voltage across the interruption device to a value that causes *di/dt* to become negative. These techniques are discussed in the following sections [39, 40].

3.1.1 Current Zero Point

One approach for interrupting a DC fault is to force a zero point in the current [39-40]. With no current flowing, a switch can be opened without fear of the development of an arc. To acquire the zero current flow, techniques involving the injection of current into the system to supply the fault have been proposed. One topology, shown in Figure 3.2, utilizes a resistor, switch, charged capacitor, and AC breaker. During normal operation or prefault conditions, the breaker is closed and current flow is admitted. However, when a fault is detected, the parallel switch is closed liberating the charged capacitor to inject current and the AC breaker to be opened.

This technique has been implemented with thyristors, and the resulting interruption device has been coined the thyristor circuit breaker (TCB) [41-43]. The TCB employs a thyristor (T1) placed in parallel with an inductor, charged capacitor, and thyristor (T2) combination as depicted in Figure 3.3. Typical operation includes the

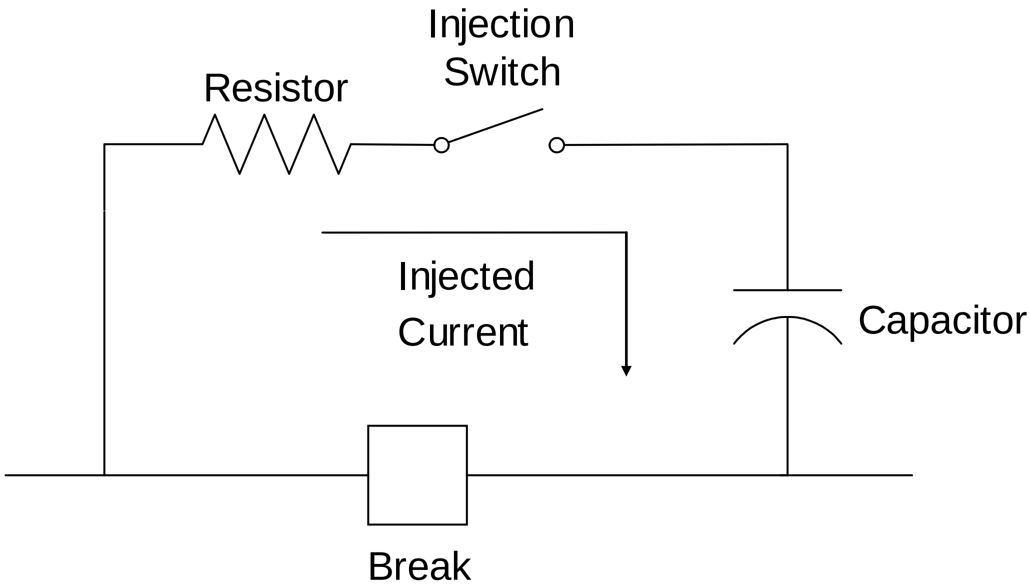


Figure 3.2 Circuit for instigating zero point [39].

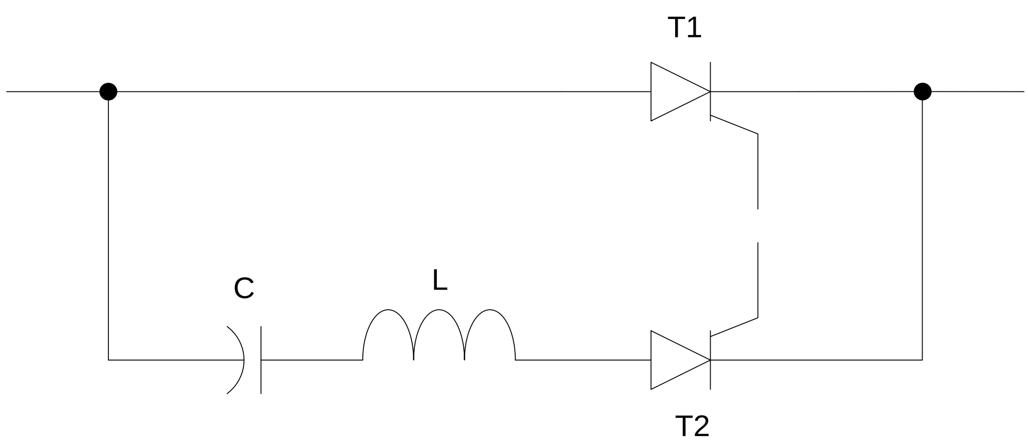


Figure 3.3 Thyristor circuit breaker [41].

constant conduction of T1 and the deactivation of T2. Once a fault is detected, T2 is activated and the capacitor is discharged into the system providing a zero point for T1. With no current flow, T1 can be disabled. This design has the associated complications of increased losses with the constant conduction of thyristor T1 and high costs due to the large capacitor necessary for injection of current. This capacitor must likewise have a voltage rating that exceeds the arc-voltage ea. A two-stage TCB has been designed to alleviate the size of the capacitor, but the design still implements a thyristor for conduction [43].

3.1.2 Increasing Arc Voltage

The voltage across the circuit protection device, *ea*, can also be harnessed to interrupt a fault. The requisite is that *ea* must adequately exceed *E-iR* to drive *di/dt* negative such that the current reaches zero. Two approaches have been devised to boost *ea*: creation of an arc and supplementary circuit protection.

A simplistic view of the arc voltage is as a function of the arc length, *d*, or distance between the interruption device points, and the fault current [40]:

$$ea = A + Bd + \frac{C + Dd}{i} \tag{3.3}$$

The values of A, B, C, and D represent the different parameters of the system, often determined empirically. These parameters are often associated with the dielectric blocking material and dimensions of the protection device.

Upon examination of the equation, an apparent conclusion is that an increase in the distance between the electrodes or a decrease in the arc current results in a larger arc voltage. From these two factors, the distance is the more straightforward to control. Hence, enlarging the distance is the basic strategy for increasing the rating in many interruption devices (such as fuses and circuit breakers.) Since the arc voltage requirements for DC are higher than those for AC, many AC interruption devices can be implemented for DC but with significantly reduced ratings [39, 40, 45]. Other methods for increasing the arc voltage include forcing the arc to take alternative paths either through mechanical means or through a magnetic field [44].

Although increasing distance is one method for raising *ea*, other schemes have been developed. Several studies have discussed the application of low-voltage AC circuit breakers for use in DC [45, 46]. Since DC requires only two transmission paths instead of the three necessitated by AC, one of the extra paths could be exercised as another interruption point in the DC path as illustrated in Figure 3.4. The addition of another break point could assist in boosting *ea* enough to interrupt the circuit. An alternative topology for implementing an AC circuit breaker for DC interruption is provided in Figure 3.5. Instead of exploiting two phases for the positive and one for the negative, all three phases are solely adopted for the positive, significantly increasing *ea*. Nevertheless, a direct correlation of AC to DC interruption potential does not exist, and the only verification of the effectiveness of a circuit breaker in DC is through testing. Furthermore, grounding one phase of DC can lead to complications with the interruption

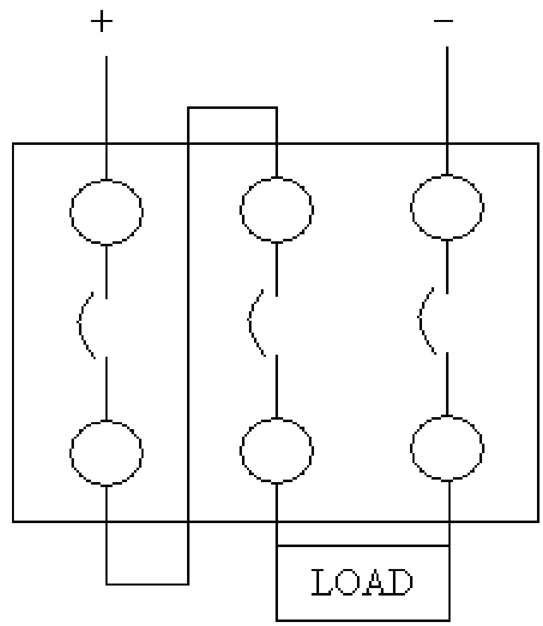


Figure 3.4 Methodology 1 for using AC circuit breakers in DC [42].

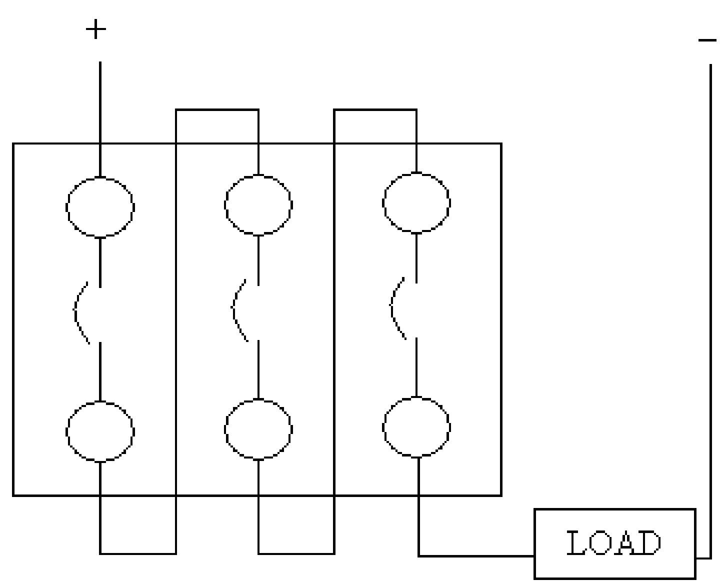


Figure 3.5 Methodology 2 for using circuit breakers in DC [42].

devices. Moreover, the standard inductive detection circuit implemented for AC fault detection does not function for DC and alternative DC fault detection technologies are necessary.

Another design that implements increasing *ea* but without the creation of an arc is depicted in Figure 3.6 [47]. In this circuit, two IGBTs and a varistor are placed in parallel with a mechanical switch. When a fault is detected, the IGBTs are forced on, clamping the voltage and permitting the mechanical switch to be turned off. The high fault current passing through the varistor instigates a high voltage by its nature creating the appearance of a large *ea* forcing di/dt to quickly decrease to zero. This approach has been successfully used in a 600V system for submarine power systems applications. Similar designs have been constructed with rewarding results [48-50].

3.2 Fuel Cell Conditioning and Converter Topologies

In the standard AC distribution system, transformers are utilized to raise and lower the voltage. These devices cannot be employed directly with DC as transformers rely on the magnetic fields created by alternating current. Hence, devices known as DC-DC converters are necessary. DC-DC converters have numerous topologies and depending on the design chosen, have the capability to raise, lower, and/or regulate the output voltage.

DC-DC converters operate through semiconductors that behave as switches. These devices activate and deactivate repeatedly, based on a control algorithm, passing a

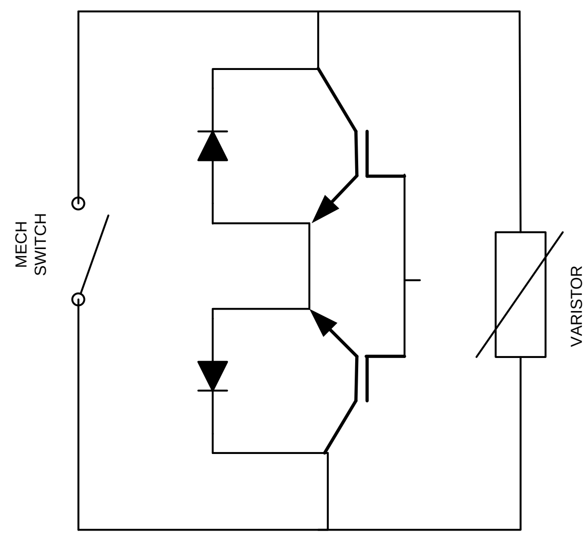


Figure 3.6 DC hybrid circuit for fault interruption [47].

supply voltage to the output. Some DC-DC converter designs directly pass the supply voltage to the output while others charge inductive elements that pass the energy to the output during another switching event. In either case, the output is a choppy waveform that is usually filtered with a capacitor as depicted in Figure 3.7.

To adopt fuel cells into the distribution system, power conditioning is necessary. Fuel cells cannot accept current in the reverse direction, do not perform well with ripple current, have a low output voltage that varies with age and current, respond sluggishly to step changes in load, and are limited in overload capabilities [7].

For these reasons, power converters are often necessary to boost and regulate the voltage as a means to provide a stiff applicable DC power source. Furthermore, application of semiconductors in standard configurations may not meet power and voltage requirements. Methods to achieve this must be examined. Accordingly, in the

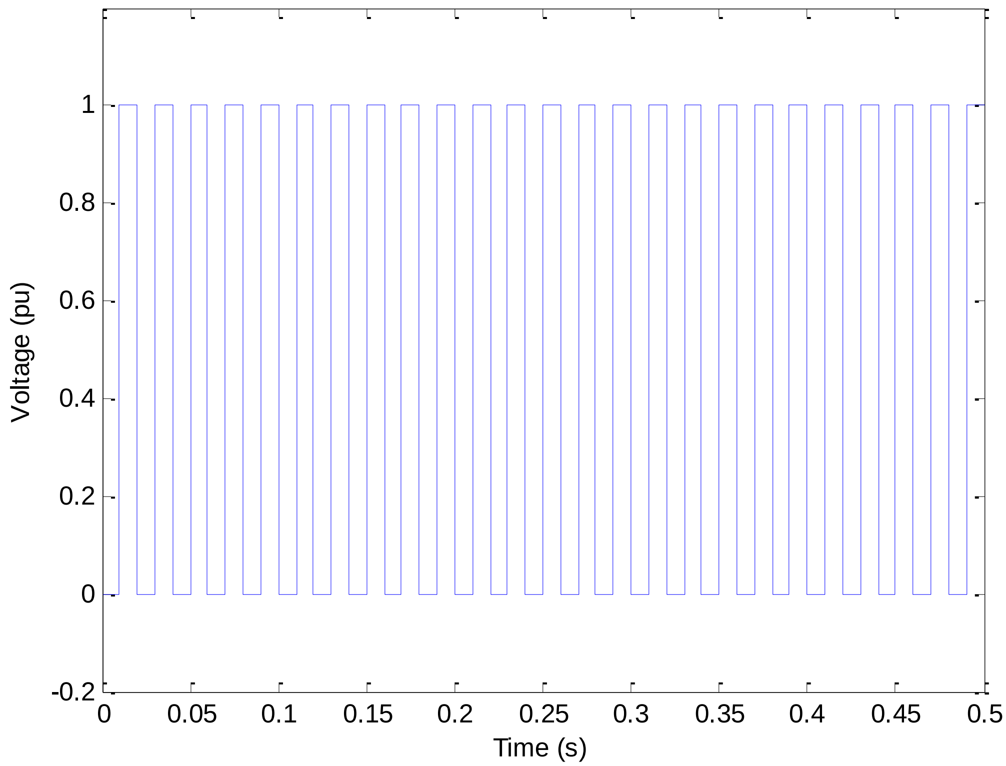


Figure 3.7 Switching example waveform.

following subsections, several DC-DC converter designs for utilization with fuel cells and system voltage conversion, a paralleling topology that increases efficiency and reliability of the DC-DC converter module, and wide-band gap semiconductors for boosting device voltage ratings are discussed.

3.2.1 Converter Topologies

As mentioned, fuel cells require power conditioning to operate effectively. For instance, to prevent reverse and ripple current, diodes and capacitors are often inserted in-between the fuel cell and DC-DC converter in the configuration shown in Figure 3.8. For large step-changes in the load, energy storage devices such as batteries and super-capacitors can provide and absorb energy as shown in Figure 3.9 [7]. These methods are simple and effective in eliminating some of the key issues with fuel cell power conditioning.

In terms of voltage conversion, the conventional configuration of a DC-DC boost converter for fuel cell power conditioning is shown in Figure 3.10. This converter has a low component count and a simple control structure as the converter has only one switch. Although this configuration is a well-known boost topology, this design does meet the criteria of electrical isolation, which is an important feature for power systems. Moreover, the large variance in magnitude between the input and output imposes severe stresses on the switch [51].

A full bridge converter, as shown in Figure 3.11, is the most frequently implemented circuit configuration for fuel cell power conditioning. This configuration implements a full bridge inverter that converts the DC voltage to AC followed by a transformer that not only has the capability to boost or reduce the voltage but provides electrical isolation. Unlike a typical AC system transformer, the size can be significant since the intermittent AC frequency can be high. Last, a rectifier bridge converts the AC to DC. This configuration provides electrical isolation and reduces stress on the switches at the cost of a higher number of components and more complicated control structure [52-54]. For electrical isolation and high boost ratio, forward, push-pull, half bridge, and full bridge converters are other options. Nevertheless, the full bridge converter is the best for

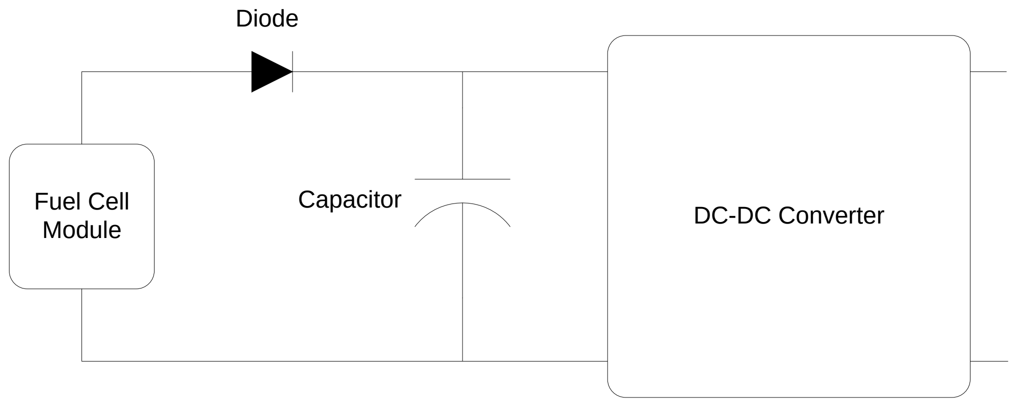


Figure 3.8. Diode and capacitor insertion for power conditioning [7].

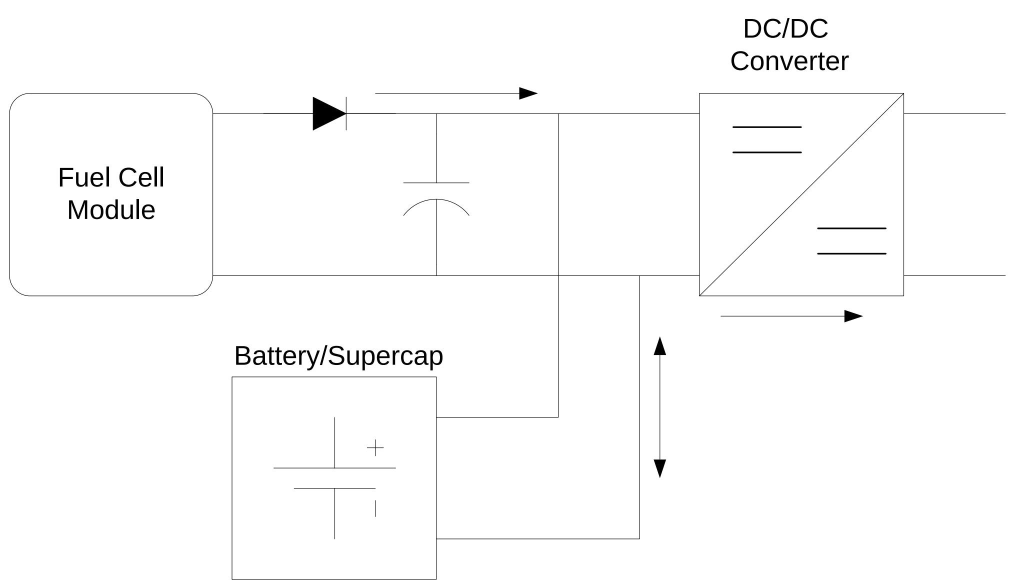


Figure 3.9. Fuel cell power conditioning with energy storage.

fuel cell power conditioning, based on the following reasons [7]:

- The full bridge converter is suitable for high power transmission since transistor voltage and current stresses are not high. Generally, push-pull and forward converters are not suitable for high power applications.
- Compared to the half-bridge, the device current rating and transformer turns ratio can both be reduced by one half.
- The full bridge converter has small input and output current and voltage ripple.
- The full-bridge topology is a favorite topology for ZVS (zero voltage switching) PWM techniques.

3.2.2 Paralleling Topology

One complication with power converters is the mediocre efficiency of operation

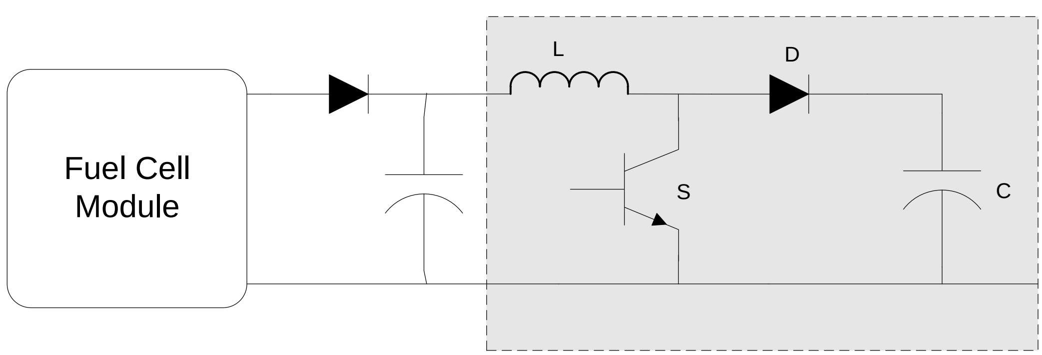


Figure 3.10 Non-isolated DC-DC boost converter for fuel cell power conditioning [51].

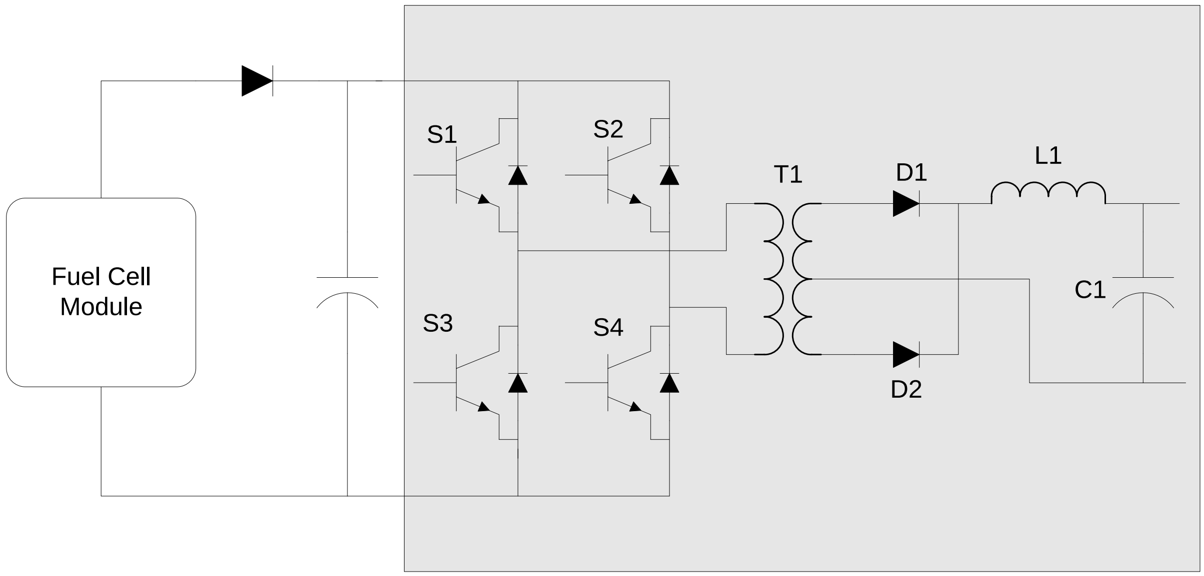


Figure 3.11 Isolated DC-DC full-bridge converter for fuel cell power conditioning [52, 53].

during moderate loading. An example curve of converter efficiency with respect to load is provided in Figure 3.12. As evident, when converters are operated below 50% of the rating, efficiency tends to be lower than the maximum. This characteristic of powerconverters can provide substandard efficiency during common operation since design of converter ratings is focused on meeting a maximum and not an average.

This efficiency curve characteristic is a combination of the effects of semiconductor switching and conduction losses. Although switching losses are relatively constant for varying loads (as frequency is the controlling factor in switching losses), the amount of conduction or on-time losses increases with rating as the transmitted power is increased. Hence, the conduction losses provide a seemingly constant efficiency, but the switching losses have the most impact during low loading [55].

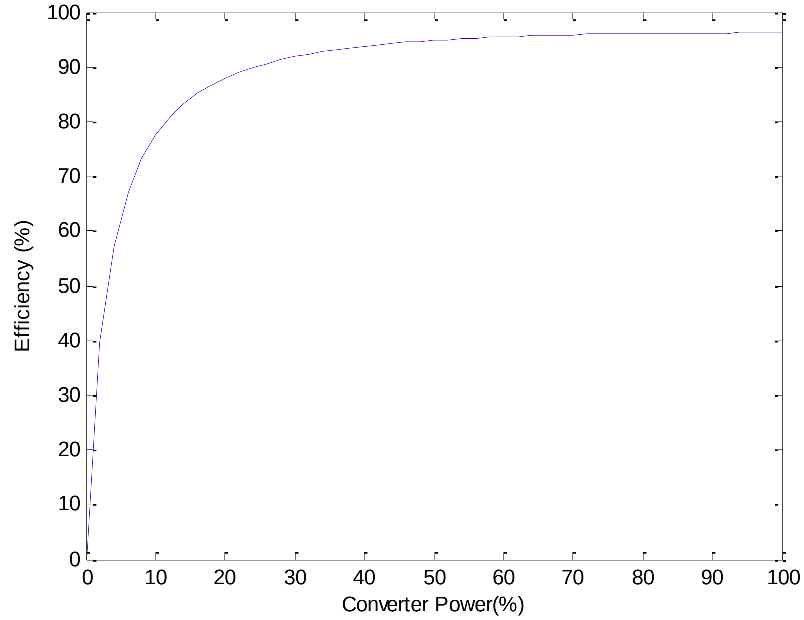


Figure 3.12 Efficiency curve for typical power converter.

Nevertheless, high efficiency throughout the operation spectrum is achievable through a conceived paralleling topology [56]. The strategy is to deactivate any excess converters thereby keeping a high load on each remaining converter. The idea is to keep the converters operating as close as possible to the rating thereby reducing the effect of the switching losses. Likewise, if extra power is necessary, the converters can be reactivated. As shown in Figure 3.13, this technique allows multiple DC-DC converters to operate close to the maximum operating efficiency until as low as 10% of operation.

Along with improving efficiency, this topology can raise the reliability. Instead of having the same converters continually operating, the converters could be cycled allowing for one converter to take on the function of another. Furthermore, paralleling

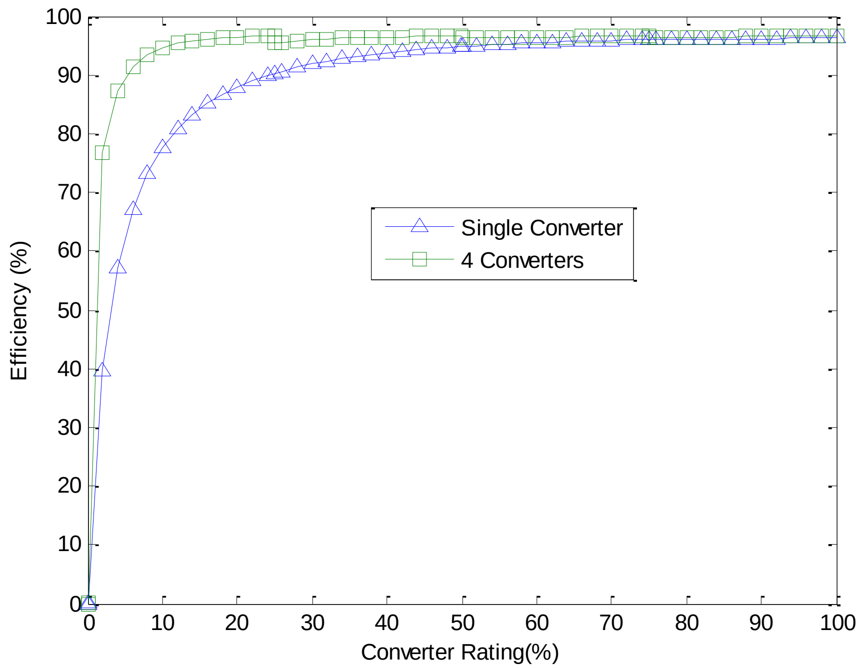


Figure 3.13 DC-DC converter efficiency curves.

converters can raise the power delivery capability without increasing the size of each device. Nevertheless, paralleling of converters adds complexity and additional cost as more devices and components are necessary.

3.2.3 Wide Bandgap Semiconductors

Another dilemma in the application of a DC distribution system is the present switching device technology. A distribution system can have voltage requirements that range from 2.5kV to 30kV. This voltage magnitude can eliminate the utilization of some particular semiconductors unless they are placed in series adding significant complexity. Likewise, designers might have to sacrifice switching speed of the semiconductors in lieu of blocking voltage [57]. Nevertheless, semiconductors manufactured from wide bandgap materials can provide the boost in blocking voltage without loss of switching speed. As shown in Table 3.1, many of the known wide bandgap materials inherently have better characteristics such as increased electric breakdown field (reverse blocking voltagecapability), thermal conductivity (the ability of the device to remove heat), and the saturated electron drift velocity (switching speed) [58]. Although research into these materials is still on-going, SiC diodes have already reached the market and are providing higher capacity devices [59].

3.1 Distribution Lines

In the power system, transmission and distribution lines carry power from generation sources, through conversion devices such as transformers or power

Table 3.1 Physical characteristics of some wide bandgap materials [58].

Property	Si	GaAs	6H-SiC	4H-SiC	GaN	Diamond
Bandgap (eV)	1.12	1.43	3.03	3.26	3.45	5.45
Electric Breakdown Field (kV/cm)	300	400	2500	2200	2000	10000
Thermal Conductivity (W/cm*K)	1.5	0.46	4.9	4.9	1.3	22
Saturated Electron Drift Velocity ($x10^7$cm/s)	1	1	2	2	2.2	2.7

electronics, and finally to loads. In comparing AC and DC systems, the number of lines and the insulation requirements are important factors to consider. The following sections examine these topics.

3.1.1 Insulation

Transmission and distribution lines are typically constructed of conductors made of aluminum or copper housed in insulation. This insulation has multiple functions including protecting the conductors from the environment and preventing short-circuits. The two most often implemented insulations for AC distribution lines are ethylene propylene rubber (EPR) and crosslinked polyethylene (XLPE) [60]. Degradation of these conductor insulations have been linked to the factors listed on Table 3.2 [61]. In examining the differences of AC and DC, frequency and voltage are the two characteristics that warrant examination.

Testing on several AC conductor samples has shown that utilizing the cables for DC results in a much higher breakdown voltage as shown on Table 3.3 [62, 63]. This result arises from the reduced discharge activity that exists with DC. The insulation behaves as a dielectric material providing electrical isolation outside the cable. Tests have

Table 3.2 Aging factors that affect insulation for cables [61].

Thermal	Electrical	Environmental	Mechanical
Maximum T Low, high ambient T Temperature gradient Temperature cycling	Voltage Frequency Current	Gases Lubricants Water/humidity Corrosive Chemicals Radiation	Bending Tension Compression Torsion Vibration

Table 3.3 Measured AC and DC breakdown voltages for 5kV XLPE cable [62].

Sample Number	DC Breakdown Voltage(kV)	AC Breakdown Voltage(kV)
1	255	73
2	255	66
3	270	66

shown that the long-time electrical strength of a dielectric material under DC conditions is significantly higher than that under AC [64]. A significant number of studies have already discussed the application of AC cables in DC, for HVDC applications and even in LV applications [23, 65-68]. Nevertheless, new installations for DC should adopt DC cables as the new cables are specifically designed for DC [69].

3.1.2 Extra Line

While AC has three lines, DC has only two. This has long been stipulated as a significant advantage for DC in cost savings. However, for installations where AC was already present, the additional conductor can be utilized in the new DC system. Three conductors allow for a positive, negative, and neutral lines. This permits the doubling of the transmitted voltage in DC without incurring a higher voltage on the individual lines as shown in Figure 3.14 [23, 65].

Figure 3.14 Cable configuration.

3.2 Chapter Summary

In this chapter, the modifications and upcoming technology that should help initiate DC distribution system have been discussed. The differences in AC and DC fault interruption were examined, and DC interruption technologies were presented. Since, fuel cells are the DG of choice for this dissertation, the PE devices best suited for power conditioning of fuel cells were critiqued along with an examination of the DC-DC converter topologies. Further enhancements of the PE devices were investigated through a paralleling topology and utilization of wide bandgap semiconductors. Last, the distribution lines were scrutinized in terms of insulation and the additional line for DC. In the next chapter, equations necessary for the analysis of an AC and DC system are reviewed. This is followed by a description of the algorithm implemented to find the optimum location for placement of DG.

4 ANALYSIS

In the previous chapters, work relating DC distribution, distributed generation, optimum placement of distributed generation, DC/DC converter topologies and control, fault interruption devices, and transmission of DC were reviewed. In this chapter, the development of algorithms for the computation of power system losses and the optimum allocation of DG sources are examined. The commercial software used to conduct the efficiency analysis is also discussed along with model assumptions.

4.1 Load Flow

The conventional method for resolving accurately the power losses in a distribution system is through load flow analysis. Load flow analysis is a computational algorithm that determines the power flow within the system under examination. For AC, real and reactive power flow is found through an assessment of the bus voltage magnitude and angle and the system admittance values. DC, however, has no reactive elements. Therefore, only real power is the primary concern and is calculated through the voltage magnitude and resistance. The following subsections describe load flow techniques for AC and DC systems.

4.1.1 AC

Each bus in an AC power system has six associated variables: voltage magnitude (V) and voltage phase (δ), real power (P_G) and reactive power (Q_G) generated, and real power (P_L) and reactive power (Q_L) consumed. From these equations, the voltage magnitude and phase and the real and reactive power generated tend to be unknown. To best demonstrate the development of the equations necessary for load flow analysis, the six bus AC system depicted in Figure 4.1 has been evaluated. In this example, a generator G1 is connected to bus 1 and supplies power through transformers (T1, T2, and T3) and distribution lines (Line 23, Line 25, and Line 35) to two loads (L1 and L2.) Utilizing the transformer and line impedance values (either from manufacturer or from experimental data), the corresponding admittance can be calculated, and the admittance diagram shown in Figure 4.2 can be assembled [70-72]. The generator and loads at this time are ignored.

In determining the voltage magnitude and angle at each bus, Kirchoff's current law is exercised. Kirchoff's current law states that "the current entering or leaving any node must sum to zero." If this law is applied to the example six bus system, the following set of equations can be developed:

$$\begin{array}{lr} BUS1 & I_{1G} = Y_{12}(V_1 - V_2) + Y_1 V_1 \\ BUS2 & 0 = Y_{12}(V_2 - V_1) + Y_{23}(V_2 - V_3) + Y_{25}(V_2 - V_5) + Y_2 V_2 \\ BUS3 & 0 = Y_{23}(V_3 - V_2) + Y_{34}(V_3 - V_4) + Y_{35}(V_3 - V_5) + Y_3 V_3 \\ BUS4 & I_{4L} = Y_{34}(V_4 - V_3) + Y_4 V_4 \\ BUS5 & 0 = Y_{25}(V_5 - V_2) + Y_{35}(V_5 - V_3) + Y_{56}(V_5 - V_6) + Y_5 V_5 \\ BUS6 & I_{6L} = Y_{56}(V_6 - V_5) + Y_6 V_6 \end{array} \tag{4.1}$$

where V_{i} represents the complex voltage at bus i, Y, the complex admittance associated with the transformer or distribution line, and I, the net injected complex current. These variables can be rearranged and placed into matrix form as:

$$\begin{bmatrix} I_{1G} \\ 0 \\ 0 \\ I_{4L} \\ 0 \\ I_{6L} \end{bmatrix} = \begin{bmatrix} Y_{12}+Y_1 & -Y_{12} & 0 & 0 & 0 & 0 \\ -Y_{12} & Y_{12}+Y_{23}+Y_{25}+Y_2 & -Y_{23} & 0 & -Y_{25} & 0 \\ 0 & -Y_{23} & Y_{23}+Y_{34}+Y_{35}+Y_3 & -Y_{34} & -Y_{35} & 0 \\ 0 & 0 & -Y_{34} & Y_{34}+Y_4 & 0 & 0 \\ 0 & -Y_{25} & -Y_{35} & 0 & Y_{25}+Y_{35}+Y_{56}+Y_5 & -Y_{56} \\ 0 & 0 & 0 & 0 & -Y_{56} & Y_6+Y_{56} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \\ V_3 \\ V_4 \\ V_5 \\ V_6 \end{bmatrix} \tag{4.2}$$

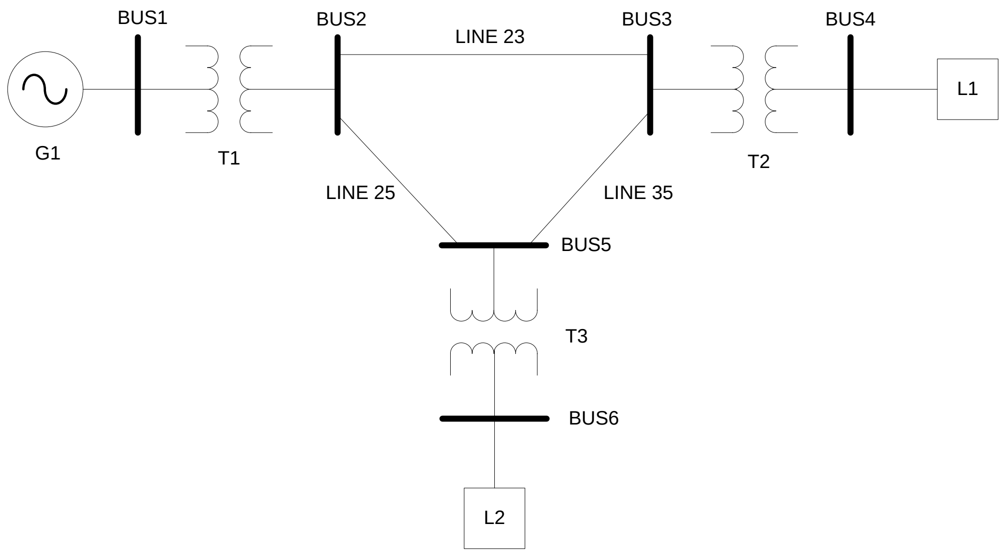


Figure 4.1. Six bus example system

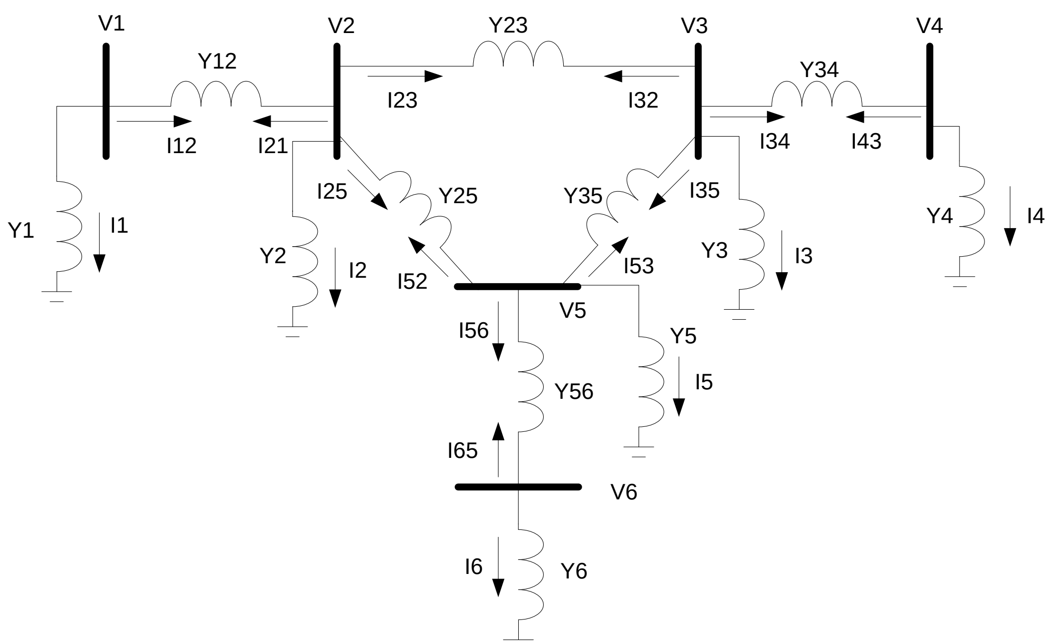


Figure 4.2 Six bus admittance example

or in simplistic terms:

$$I = YV \tag{4.3}$$

Here, I represents the net injected complex current vector, Y is a matrix composed of complex admittance values and otherwise known as the admittance matrix, and V is a vector representing the complex voltage. Another form of the matrix represented in 4.2 is given as follows [71]:

$$\overline{I}_i = \sum_{j=1}^{n} \overline{Y}_{ij} \overline{V}_j \tag{4.4}$$

In this equation, I_i represents the ith position in the net current injection vector, Y_{ij} the (i, j) position in the admittance matrix, V_j the jth position in the bus voltage vector, and n is the number of buses. The overscore depicts that the variable is complex. Expressing 4.4 in terms of magnitudes and angle [71]:

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \angle(\theta_{ij} + \delta_j) \tag{4.5}$$

For this equation, θ_{ij} is the phase angle associated with the admittance component in the (i, j) position of Y and δ_j is the phase angle associated with the voltage. An equation relating the real and reactive power to current and voltage is given [70, 71]:

$$\overline{S_i} = P_i + jQ_i = \overline{V_i}\,\overline{I_i}\,* \tag{4.6}$$

Note that P_i and Q_i are the real and reactive power at bus i, and * indicates the conjugate operation. Substituting equation 4.5 into 4.6 and expressing all the terms in magnitudes and angles [70-72]:

$$P_i + jQ_i = (V_i \angle \delta_i) \sum_{j=1}^{n} Y_{ij} V_j \angle(-\theta_{ij} - \delta_j) \tag{4.7}$$

The real and reactive power can be separated into two equations by separating the real and imaginary components [70-72]:

$$P_i = V_i \sum_{j=1}^{n} V_j Y_{ij} \cos(\delta_i - \delta_j - \theta_{ij}) \tag{4.8}$$

$$Q_i = V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \sin(\delta_i - \delta_j - \theta_{ij}) \tag{4.9}$$

As evident, these equations contain nonlinear elements and demand an iterative approach. In the following subsection, the Netwon Raphson Method is discussed. This iterative algorithm is frequently employed for solving nonlinear equations.

4.1.2 Newton Raphson Method

The Newton Raphson method is a method adopted for solving nonlinear algebraic equations through approximations of the Taylor series expansion. Consider a single dimensional function with an output c [71]:

$$f(x) = c \tag{4.10}$$

If an initial guess is made that is within close proximity to the solution, there is a deviation from the actual solution or [71]:

$$f(x^0 + \Delta x) = c \tag{4.11}$$

where x^0 represents the guess and Δx is the deviation. If this equation is expanded through the Taylor series around x^0 the following equation is obtained [71]:

$$f(x^0) + \left(\frac{df}{dx}\right)^0 \Delta x + \frac{1}{2!}\left(\frac{d^2 f}{dx^2}\right)^0 (\Delta x)^2 + \cdots = c \tag{4.12}$$

Since x^0 is relatively close to the solution, Δx should be small and the higher order terms of Δx can be neglected. As a result, the equation can be rewritten and simplified as [71]:

$$c - f(x^0) \approx \left(\frac{df}{dx}\right)^0 \Delta x \tag{4.13}$$

Note that 4.13 is a linear equation, with unknown variable Δx. In this case, an approximation for Δx can be found by rearranging the equation into the form [71]:

$$\Delta x^0 = \frac{c - f(x^0)}{\left(\frac{df}{dx}\right)^0} \tag{4.14}$$

Since the exact Δx has not been found, the process should be repeated, to obtain a more accurate result. The next estimate, x^1, is given by [71]:

$$x^1 = x^0 + \Delta x^0 \tag{4.15}$$

Returning this value into equation 4.10 with expectation of another deviation from the actual solution [71]:

$$f(x^1 + \Delta x') = c \tag{4.16}$$

where ' signifies that the Δx from equation 4.16 is not the same as that of 4.11. This process is repeated until the solution converges (Δx approaches zero).

This process can be performed on multiple variables as demonstrated by the following set of equations [71]:

$$\begin{aligned} f_1(x^0) + \left(\frac{df_1}{dx_1}\right)^0 \Delta x_1 + \left(\frac{df_1}{dx_2}\right)^0 \Delta x_2 = c_1 \\ f_2(x^0) + \left(\frac{df_2}{dx_1}\right)^0 \Delta x_1 + \left(\frac{df_2}{dx_2}\right)^0 \Delta x_2 = c_2 \end{aligned} \tag{4.17}$$

This appears as a system of linear equations with Δx_i as variables, and therefore can be solved through linear system analysis techniques.

4.1.3 AC Bus Types

Buses in an electrical system can be placed under three categories, swing bus, load bus, or voltage control bus, depending on the nature of the bus. Choosing the type of bus is the first step in solving a complex network. Table 4.1 contains the known and unknown variables in the system based on bus type.

The swing bus, also known as the reference bus, is the bus that contains the variable generation source. For this type of bus, the amount of real and reactive power generated is unknown, but the real and reactive power consumed by loads and voltage magnitude and angle are specified. The voltage magnitude and phase are usually given values of 1 p.u. and 0 respectively.

The load bus is the most common bus type in the power system. Values of the real and reactive power injected and consumed at this bus are specified whereas the voltage magnitude and angle are unknown. The injected power is generally considered zero, as a swing bus would determine the necessary power.

The last bus type is the voltage control bus and is not commonly implemented. This bus type has specified values of the voltage magnitude, real power injected, and the real and reactive power consumed. The unknowns are the voltage angle and reactive power injected [70].

Table 4.1 Specified and free variables for different bus types in AC.

	Specified	Free
Swing Bus	P_l, Q_l V = 1 pu $\delta = 0^o$	P_g, Q_g
Load Bus	$P_g = Q_g = 0$ P_l, Q_l	V, δ
Voltage Control Bus	P_g, P_l, Q_l, V	Q_g, δ
P_g = real power generated Q_g = reactive power generated P_l = real power consumed	Q_l = reactive power consumed V = voltage magnitude δ = voltage angle	

4.1.4 Newton Raphson Method Applied to AC Equations

As noted previously, the AC system equations are nonlinear and require an iterative approach such as the Newton Raphson Method. Summing the net injected real and reactive power with the real and reactive power supplied or consumed by the load and generator yields [70-72]:

$$\Delta P_i = P_{Gi} - P_{Li} - V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \cos(\delta_i - \delta_j - \phi_{ij}) = 0 \tag{4.18}$$

$$\Delta Q_i = Q_{Gi} - Q_{Li} - V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \sin(\delta_i - \delta_j - \phi_{ij}) = 0 \tag{4.19}$$

These equations can be converted into a linear form through implementation of the Newton Raphson Method as follows:

$$\frac{\Delta P}{d\delta}\Delta\delta + \frac{\Delta P}{dV}\Delta V = \Delta P \tag{4.20}$$

$$\frac{\Delta Q}{d\delta}\Delta\delta + \frac{\Delta Q}{dV}\Delta V = \Delta Q \tag{4.21}$$

These equations can be rewritten in matrix form as:

$$\begin{bmatrix} \frac{\partial \Delta P}{\partial \delta} & \frac{\partial \Delta P}{\partial V} \\ \frac{\partial \Delta Q}{\partial \delta} & \frac{\partial \Delta Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \tag{4.22}$$

or

$$Jx = b \tag{4.23}$$

where J is known as the Jacobian matrix and x is the solution. Essentially, an initial guess for the unknown variables is made, generally 1 p.u. for the voltages and 0 for the phase angle. Using the initial guess, the values in the Jacobian and b matrices are determined and the solution to $Jx = b$ is found. The solution x is added to the previous state (guess) and the process is repeated with each new solution substituted for the original guess until the solution converges.

$$\begin{bmatrix} \delta^{k+1} \\ V^{k+1} \end{bmatrix} = \begin{bmatrix} \Delta \delta^{k} \\ \Delta V^{k} \end{bmatrix} + \begin{bmatrix} \delta^{k} \\ V^{k} \end{bmatrix} \tag{4.24}$$

4.1.5 AC System Losses and Power Flow

Once the voltage magnitude and phase for each unknown bus has converged, the power flow and losses within the system can be calculated. The generated real and reactive power is the net injected power at the swing bus plus the power consumed by any loads or [70-72],

$$P_{Gi} = P_{Li} + V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \cos(\delta_i - \delta_j - \phi_{ij}) \tag{4.25}$$

$$Q_{Gi} = Q_{Li} + V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \sin(\delta_i - \delta_j - \phi_{ij}) \tag{4.26}$$

The losses in the system can be computed by calculating the difference in generation and load [70-72]:

$$P_{Losses} = \sum P_{gen} - \sum P_{load} \tag{4.27}$$

The real and reactive power flow through each branch can be established through the following equations [70-72]:

$$P_{ij} = V_i V_j Y_{ij} \cos(\delta_i - \delta_j - \phi_{ij}) - V_i^2 Y_{ij} \cos(\phi_{ij}) \tag{4.28}$$

$$Q_{ij} = V_i V_j Y_{ij} \sin(\delta_i - \delta_j - \phi_{ij}) - V_i^2 Y_{ij} \sin(\phi_{ij}) \tag{4.29}$$

4.1.6 DC

While the AC system has six associated variables with each bus, a DC system is composed of only three, real power consumed (P_L), real power generated (P_G), and voltage magnitude (V). This is a consequence of the absence of reactive elements in DC which results in the disappearance of the variables reactive power generated, reactive power consumed, and voltage angle. An example DC system is shown in Figure 4.3. For steady state analysis only resistance is necessary. A resistance network that represents the six bus example is shown in Figure 4.4. As was the case with AC, a matrix system can be created and equations for power flow can be developed. The equation for current in terms of the system parameters is given by:

$$I = \frac{V}{R} \tag{4.30}$$

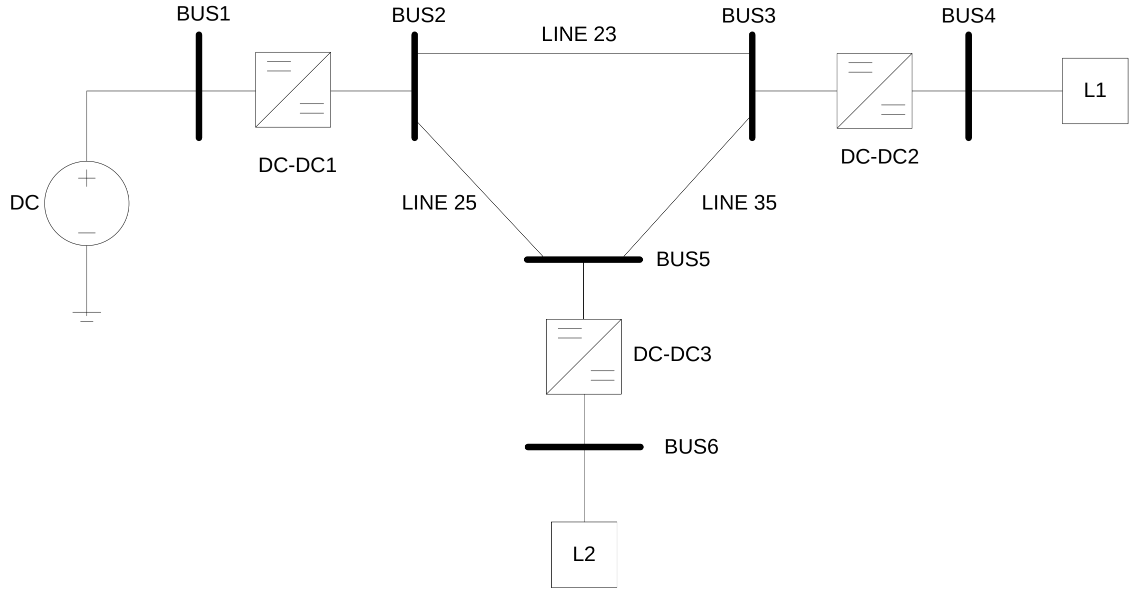


Figure 4.3 Six bus example DC system

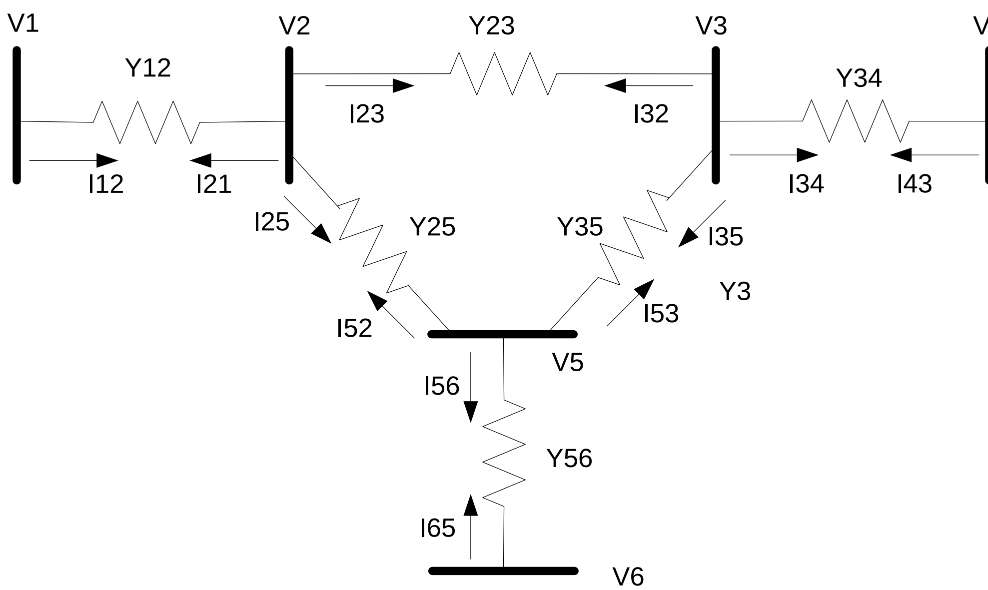


Figure 4.4 Six bus resistance network

The equation for power for a DC system is provided by:

$$P = VI \tag{4.31}$$

Combining the equations, an equation relating the system parameters to power flow is given as:

$$P = V_i \sum_{j=1}^{Nbus} \frac{V_j}{R_{ij}} \tag{4.32}$$

4.1.7 Bus Types for DC

Since DC systems do not have reactive power, DC buses are limited to the two categories, slack bus and load bus. Table 4.2 contains the known and unknown variables in a DC system based on bus type.

The swing bus, also known as the reference bus, is the bus that contains the variable generation source. For this type of bus, the amount of real power generated is unknown, but the real power consumed by loads and voltage magnitude are specified. The voltage magnitude is usually given a value of one.

The load bus is often the most common bus type in the power system. Values of the real power injected and consumed at this bus are specified whereas the voltage magnitude is unknown.

Table 4.2 Specified and free variables for different bus types in DC

	Specified	Free
Swing Bus	Pl V = 1 pu	Pg
Load Bus	Pg, Pl	V

4.1.8 Newton Raphson Method Applied to DC Equations

For DC systems, the basic load flow equations are similar to those of the AC load flow except that there is no voltage angles (δ), no reactive power (Q), and the lines are composed of purely real elements. Hence, only one equation exists for the net power leaving a bus and is given by:

$$\Delta P_i = P_{Gi} - P_{Li} - V_i \sum_{j=1}^{Nbus} \frac{V_j}{R_{ij}} = 0 \tag{4.33}$$

As with the case of the AC model equations, the DC equation is linearized in terms of ΔV by taking the derivative. In matrix form this is

$$\left[\frac{\partial \Delta P}{dV}\right] \Delta V = \Delta P \tag{4.34}$$

or

$$Jx = b \tag{4.35}$$

where J is known as the Jacobian matrix and x is the solution. Essentially, an initial guess for the unknown variables (bus voltages) is made, generally 1 p.u. Using the initial guess, the values in the Jacobian and b matrices are determined and the solution to $Jx = b$ is found. The solution x is added to the previous state (guess) and the process is repeated with each new solution substituted for the original guess until the solution converges. In this case x is ΔV.

$$V^{k+1} = \Delta V^k + V^k \tag{4.36}$$

4.1.9 DC System Losses and Power Flow

Once the solution voltage magnitude and phase have converged, the power flow and losses within the system can be determined. The amount of power generated at bus i is given by:

$$P_{Gi} = P_{Li} + V_i \sum_{j=1}^{Nbus} V_j Y_{ij} \tag{4.37}$$

The losses in the system can be determined by calculating the net generation and subtracting the net load or:

$$P_{Losses} = \sum P_{gen} - \sum P_{load} \tag{4.38}$$

The power flow for each branch is given by:

$$P_{ij} = V_i V_j Y_{ij} - V_i^2 Y_{ij} \tag{4.39}$$

4.2 Genetic Algorithm

Optimization of the placement of DG in this study is performed through the genetic algorithm (GA). GA is an evolutionary technique that finds an optimum through applying a natural selection approach. In other words, those traits that are inherently better in a parent will be passed to their offspring. GA operates by creating a random pool (population) of possible choices for solutions (individuals), otherwise known as parents. The parents are utilized in two evolutionary processes, crossover and mutation, to create offspring. These offspring are applied in the creation of a new pool. As each generation is created, the parents and offspring approach an optimum. The following sections describe the mutation and crossover techniques [73-75].

4.2.1 Crossover

The evolutionary process known as crossover involves the blending of two parents as shown in Figure 4.5. These parents are chosen randomly from the pool and are exploited in the development of two new distinct offspring. The following subsections describe the varying crossover techniques implemented.

4.2.1.1 Arithmetic Crossover

In arithmetic crossover a weighted average is applied to the two parents to determine the new offspring. This weighted average is determined randomly and must lie between 0 and 1:

$$0 \leq \lambda \leq 1 \tag{4.40}$$

The following equations are applied to generate the new offspring:

$$c_1 = \lambda p_1 + (1-\lambda) p_2 \tag{4.41}$$

$$c_2 = (1-\lambda) p_1 + \lambda p_2 \tag{4.42}$$

Here c_1 and c_2 represent the offspring, p_1 and p_2 the parents, and λ the weighted average.

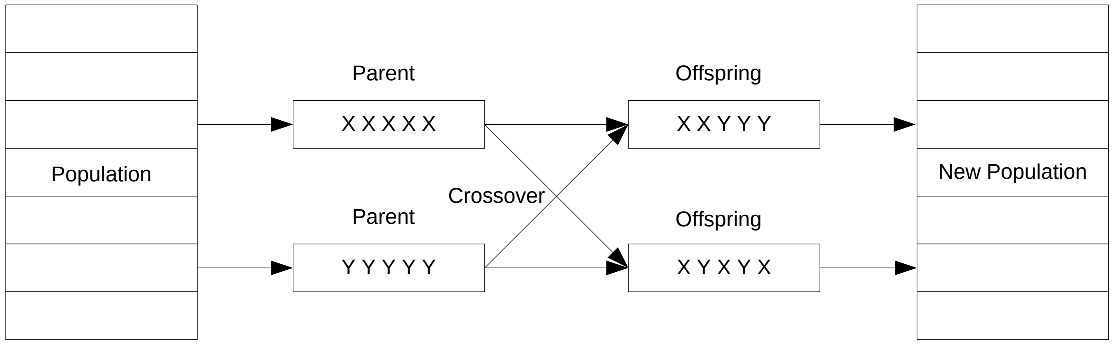


Figure 4.5 Crossover

4.2.1.2 Simple Crossover

With simple crossover, segments of the parents are attached to create the offspring. The position of the break in the parents, M, is chosen randomly based on the number of possible solutions, N,

$$0 \leq M \leq N \tag{4.43}$$

The following equations are applied to generate the new offspring:

$$c_1 = [p_1(1:M) + p_2(M:N)] \tag{4.44}$$

$$c_2 = [p_2(1:M) + p_1(M:N)] \tag{4.45}$$

Again, c_1 and c_2 represent the offspring while p_1 and p_2 represent the parents.

4.2.1.3 Heuristic Crossover (Direction-Based Crossover)

In this method, the two parents are identified based on a ranking. The ranking is contingent on the solution that the parents provide to the problem. The parent with the most dominant trait, in this case p_2, is given priority in the new offspring. The equation is as follows:

$$c = \lambda(p_2 - p_1) + p_2 \tag{4.46}$$

As before, c represent the offspring, p_1 and p_2 the parents, and λ is a number picked randomly between 0 and 1.

4.2.2 *Mutation*

While crossover techniques involve two parents, mutation requires only one parent. The objective of mutation is to create offspring that might be outside the local minimum or maximum such that a global minimum or maximum can be located. As shown in Figure 4.6, mutation alters the makeup of the parents randomly based on several different methods to create new offspring. The mutation methods implemented are discussed in the following subsections.

4.2.2.1 *Boundary Mutation*

The boundary mutation is the most simple of the mutations utilized. In this mutation technique, the respective makeup of the parents is completely ignored. Instead, the new offspring is created based on the minimum or maximum limit imposed on the parents. In this way, those offspring that are missed by the crossover technique are realized through this methodology.

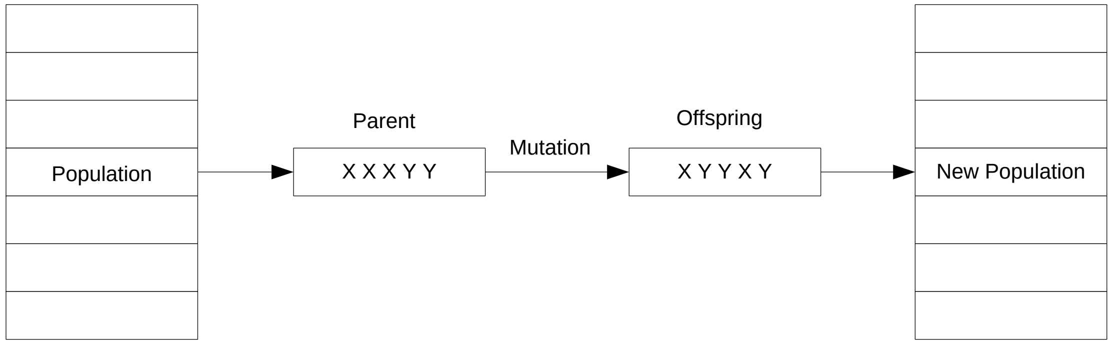


Figure 4.6 Mutation.

4.2.2.2 Non-uniform Mutation and Multi-Non-uniform Mutation

The non-uniform and multi-non-uniform mutations change the characteristics of a parent based on a non-uniform probability distribution curve. This Gaussian distribution starts wide and narrows as the current generation approaches the maximum generation. The distribution curve provides a change that is added to parent:

$$\Delta = y(\lambda(1-r))^{b} \tag{4.47}$$

The variables Δ, y, λ, r, and b, represent the change in the parent, maximum allowable change, a random number between 0 and 1, the ratio between the current generation and maximum generation, and a shaping parameter. To generate the new offspring this change is added to the particular characteristics of the parent. Non-uniform mutation only alters one characteristic while multi-non-uniform changes all the characteristics of the parent.

4.2.2.3 *Uniform Mutation*

The uniform mutation changes a single characteristics of a parent based on a uniform probability distribution curve.

4.2.3 *Optimizing Population*

During the creation of the new population from the old population, a record of the best and worst offspring is stored. Once a new population has been finalized, the worst member in the new population is replaced with the best member in the population. This moves the population towards a more optimum solution.

4.2.4 *Governing Variables in GA*

With GA several variables must be defined to fully utilize the algorithm. These variables include: the number of entities in the population, the number of generations that should be created, and the number of solutions pursued. These constraints determine the speed and accuracy of the GA model. A small population with a short number of generations will determine a solution quickly but will most likely not result in the most optimum solution. This tradeoff must be evaluated by the designer.

4.2.5 *Genetic Algorithm Applied to DG Optimization*

In this study, the main application of GA focuses on applying a chosen amount of generation at optimal locations based on system losses. The implemented code can be found in Appendix E. The bus locations for optimized placement of DG are input as the population and the resulting system loss, calculated through the DC load flow equations previously discussed, is determined. Since the algorithm seeks to maximize this value, the losses were made negative.

To ensure accuracy, the GA variables population and number of generations were increased as more locations for optimized placement of DG were sought. For instance, the size of the population was set to 500 and was increased by 500 after 5 optimum locations were found. The number of generations was equated to 20 and increased by 10 with each iteration. While these constraints increased the accuracy, the amount of computational time also grew.

As an example, consider a 70 bus system. The first step is to generate a list of parents (bus numbers), which the genetic algorithm does randomly. The parents are evaluated based on placement of DG on that bus and the best (lowest losses) and worst (highest losses) cases are stored. Out of the list of parents, suppose that the algorithm chooses the two parents as 65.5 and 31.6. (The algorithm is allowed to choose any number between 1 and 70. These numbers are rounded when entered into the load flow). Further suppose that based on the 70 bus system, bus 48 and bus 22 were the worst and best case out of the pool. If the algorithm is utilizing the arithmetic crossover and λ is chosen randomly to be 0.717, the results would be:

$$c_1 = \lambda p_1 + (1-\lambda) p_2 = (0.717)(65.5) + (1-0.717)(31.6) = 55.9$$

$$c_2 = (1-\lambda) p_1 + \lambda p_2 = (1-0.717)(65.5) + (0.717)(31.6) = 41.2$$

and the two bus locations that become offspring are 56 and 41. These bus numbers are input into the DC load flow algorithm to determine the network losses and reinserted back into the pool. Here are the possible care scenarios:

- Bus 41 or bus 56 has a higher loss than the worst case bus 48. This bus would be replaced by the best case bus 22 in the pool.
- Bus 41 or bus 56 has a lower loss than the best case bus 22. This bus would replace the worst case bus 48 in the pool and become the best case bus.
- Bus 41 or bus 56 are in-between bus 22 and bus 48 in terms of losses. The worst case bus 48 would be replaced by the best case bus 22.

To illustrate the random behavior of GA in locating an optimum location, a test DC system of 46 buses was also constructed and evaluated. In this particular case, the population was set equal to the number of buses and the number of generation was equated to 38. Figure 4.7 and Figure 4.8 show the optimization of losses in relation to the number of iterations of the example system with two independent runs. Each line in the graph represents a different member of the population and as shown converge onto a single solution.

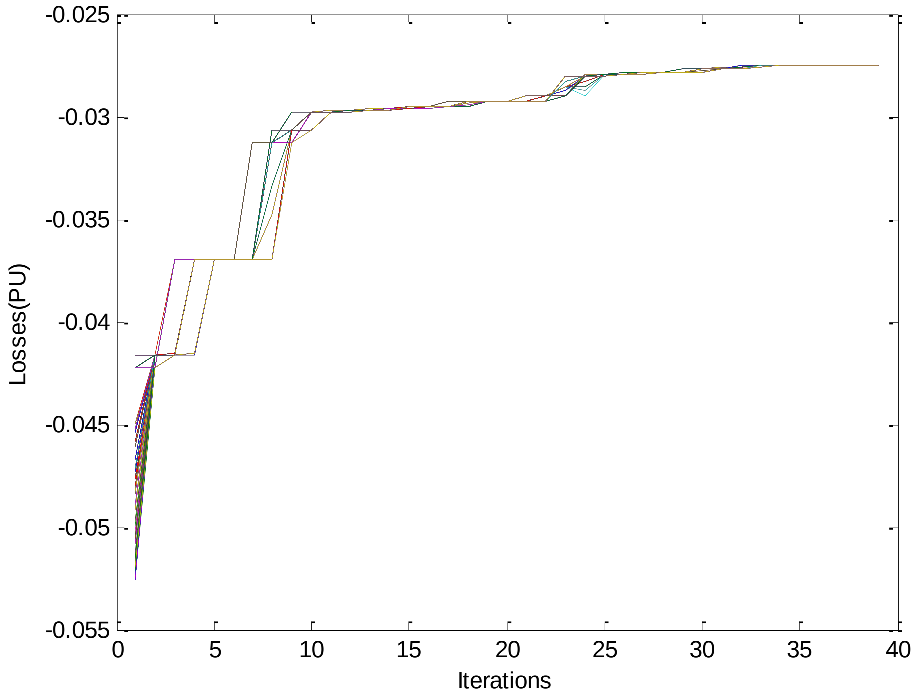


Figure 4.7. GA minimization of losses run 1

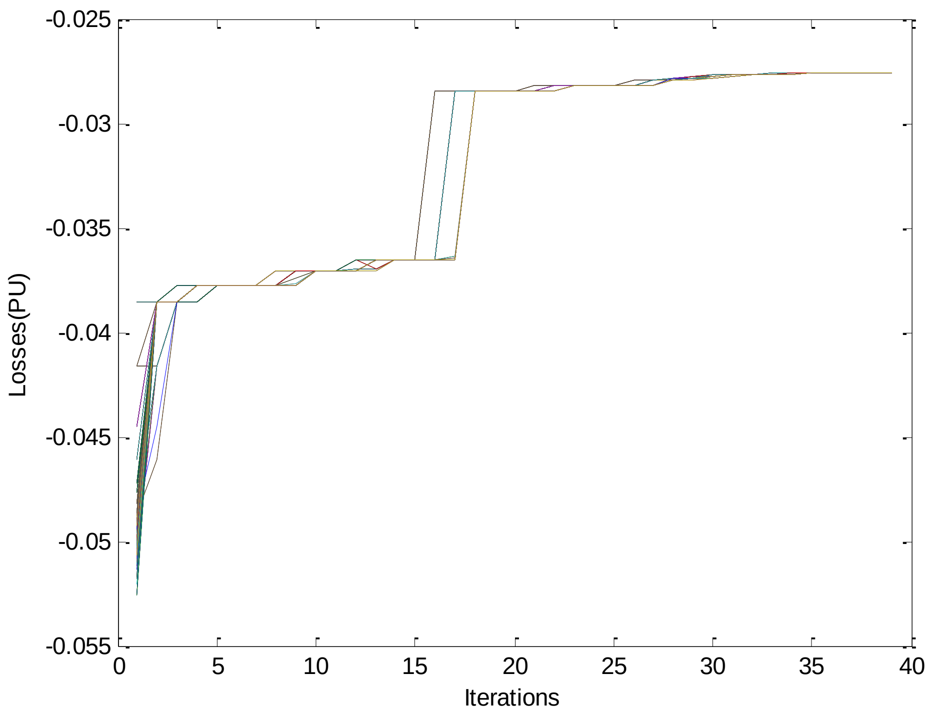


Figure 4.8. GA minimization of losses run 2

Several key features to note based on these results:

- The losses are made negative since the GA algorithm functions based on locating a maximum.
- The initial population has much higher losses than the final results. The algorithm is locating an optimum.
- Both results although taking varying paths with different starting populations arrive at the same solution.
- Eventually a plateau in the loss calculation is reached indicating that the GA has reached a solution.

Figure 4.9 shows the corresponding optimization of the bus location. As the GA searches for an optimum the population converges on to a particular solution. In this case, bus 33 was found to be the optimum location.

4.3 SKM Software

The software package, SKM, was applied to conduct the initial efficiency analysis comparison. This was done for several reasons. First, the software is employed for conducting load flow and has an extensive library of system component parameters. The broad library and the ability to construct the system with visual blocks grants SKM

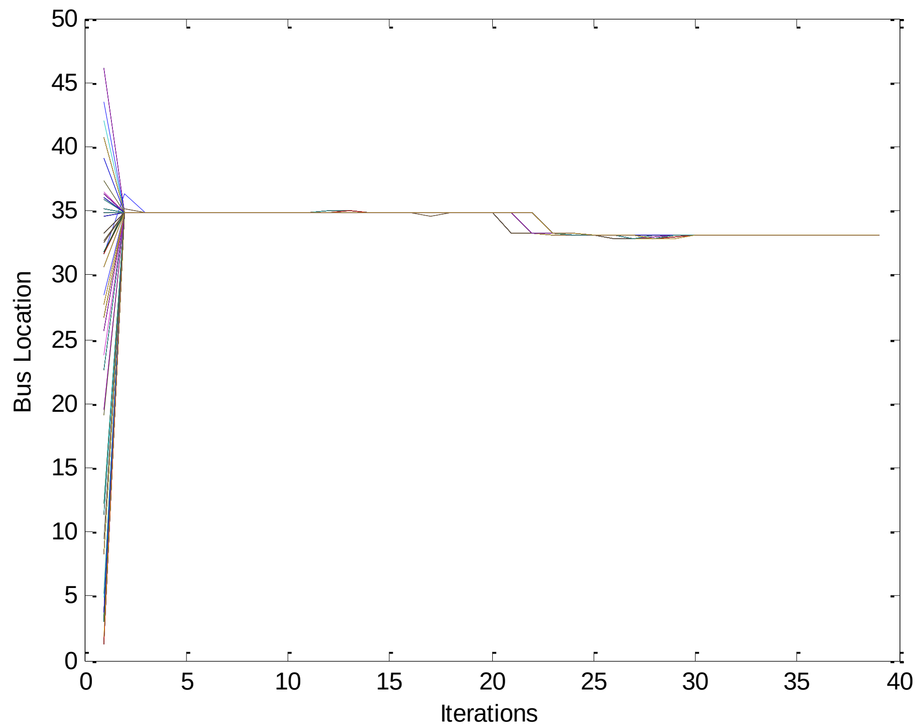


Figure 4.9. Locating the optimum bus location with GA

advantages over other load flow software. The use of this software also afforded insight into the limitations of the available software packages. The following sections describe the AC and DC system parameters provided for analysis in SKM and problems that were encountered while using the software.

4.3.1 AC

In the AC system, distribution lines, loads, transformers, and capacitor banks provide the primary components examined in load flow. Table 4.3 shows a schematic representation of the building blocks provided in SKM. Each component is associated with parameters for performing load flow. These are listed in Table 4.4.

Since the base equations are nonlinear, an iterative numerical technique must be implemented to solve for the solution. The numerical analysis method implemented by SKM has been coined the "double current injection" method. In this method, the losses are originally assumed to be zero, and the current is determined through calculation from the load and nominal voltage values. The losses are then included and the voltage drop at each load and bus is determined. The new voltages lead to a recalculation of the current. This process is repeated to a minimum error has been reached [78].

Table 4.3 Select AC component representations in SKM

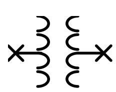
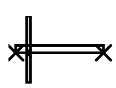
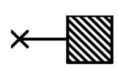
Transformer	AC Distribution Line	AC Load	Fault Protection	AC Bus
				

Table 4.4 AC SKM input parameters

Distribution Line	Zero Sequence Impedance Positive Sequence Impedance
Load	Apparent Power Power Factor Voltage Rating
Transformer	Zero Sequence Impedance Positive Sequence Impedance Power Rating Input/Output Voltage Rating
Capacitor Bank	Zero Sequence Capacitance Positive Sequence Capacitance

The AC losses in SKM are calculated through use of the current and impedance values. The real power loss and reactive power absorbed are determined by the following equations:

$$P_{LOSS} = I^2 R \tag{4.48}$$

$$Q_{LOSS} = I^2 X \tag{4.49}$$

4.3.2 DC

With DC analysis in SKM, the primary components are the distribution line, dc/dc converter, and load. The SKM representation of these components is provided in Table 4.5. These components are primarily modeled as resistive elements as shown in Table 4.6. Unlike in the AC system analysis, SKM employs the Newton-Raphson method to solve for the system parameters. SKM also does not directly provide the amount of losses. To calculate system losses in DC, the total load must be subtracted from the calculated generation.

Table 4.5. Select DC component representations in SKM

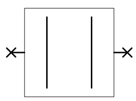
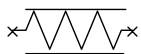
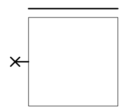
DC/DC Converter	DC Distribution Line	DC Load	DC Bus
			

Table 4.6 DC SKM input parameters

Distribution Line	$r_{cable} \times l$
Load	$\frac{V^2}{P}$
DC-DC Converter	$(1-\eta)\frac{V^2}{P}$

r_{cable} – resistance/ft
l – length of cable in ft
V – rated voltage
P – rated power
η - rated efficiency

4.3.3 Converting AC components to DC

When developing the DC model in SKM from the AC model, the transformer, AC line, and AC load were interchanged for the DC/DC converter, DC line, and DC load. This is shown in Figure 4.10. The fault interruption components were ignored as these components do not add any value to the basic load flow algorithm.

4.3.4 Problems Encountered with SKM

Although SKM is a widely used software package by industry, several problems were encountered with its use. First, during the initial creation and load flow verification of a DC system, the software crashed without warning. These errors were finally linked to several of the components applied to model the DC system and were fixed after contacting the SKM support team.

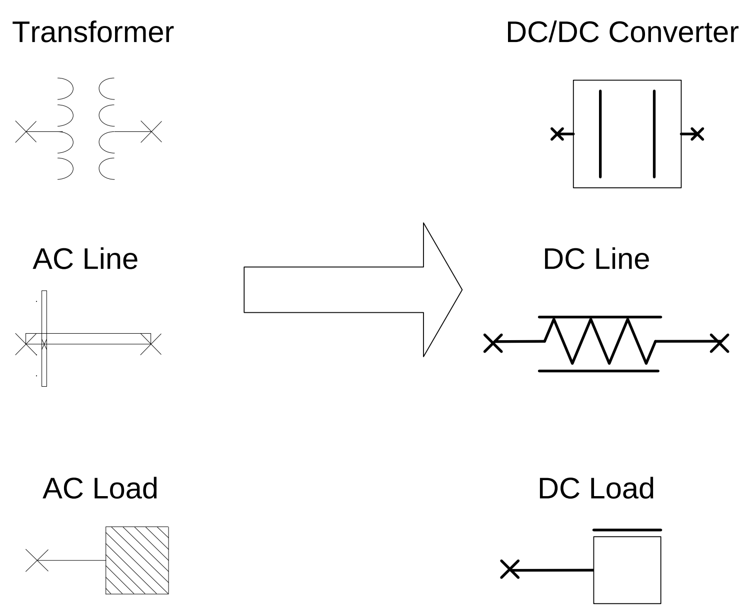


Figure 4.10 Component interchange

Another set of dilemmas was found when implementing SKM. First, SKM cannot conduct AC and DC analysis concurrently. Hence, when considering system with both AC and DC components, aggregated models were necessary to find the losses in the system. Second, the model for the DC/DC converter was often inaccurate and the inverter and rectifier models did not recognize the connected system and thereby did not function. Therefore, separate loss calculations and aggregation methods were employed to evaluate the system losses. This is discussed in the following sections.

4.4 Matlab

To utilize the genetic algorithm in finding the optimum bus locations for DG based on system losses of a DC system, a method for communicating between the genetic algorithm and losses became necessary. (The genetic algorithm needs a loss estimate in order to rank the best and worse case.) As such, a load flow algorithm utilizing the Newton Raphson equations discussed was coded and written in Matlab. A flow chart describing the algorithm is shown in Figure 4.11. The initial step required the development of resistance values for the various conductors and creation of an admittance matrix. Fixed generation values associated with any DG and all loads were also incorporated into P_G and P_L vectors in which the Newton Raphson equations would refer. All the values are per-unitized for evaluation on a scale of one. The initial values for voltage are set to one and were inserted likewise in a voltage vector. Finally, the Newton Raphson algorithm was implemented.

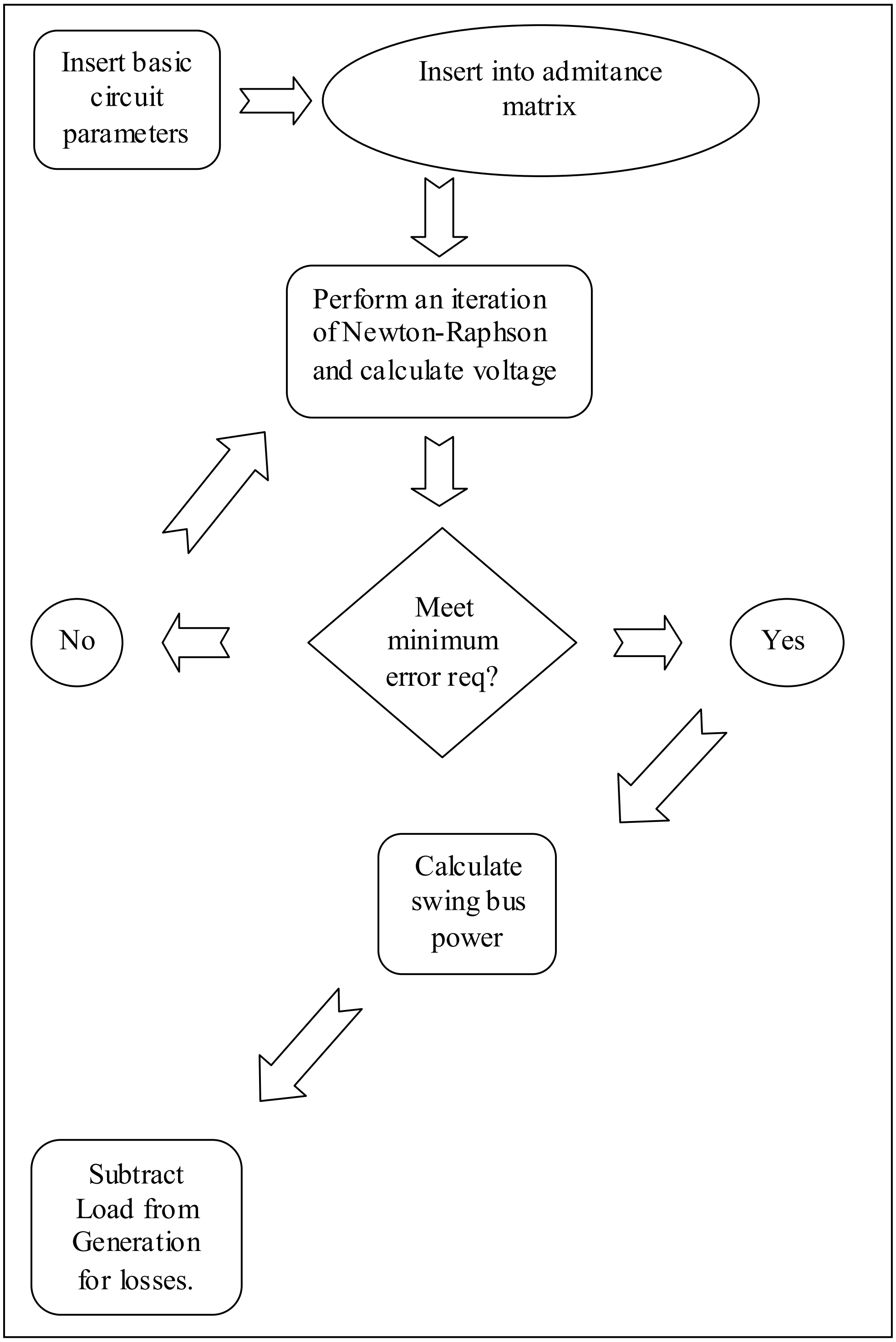


Figure 4.11 Matlab load flow algorithm model.

If the algorithm meets the minimum error requirements (Equation 4.33 is approaching zero) than the algorithm proceeds to calculate the swing bus power, otherwise another iteration of Newton Raphson is conducted. This process is repeated until the voltage on the bus converges or a significant number of iterations has been conducted and their appears to be no solution. Once the swing power has been determined, the total system losses can be evaluated by subtracting the total load from the total generation.

This loss evaluation algorithm was as the cost function for the genetic algorithm. For each generation and population member, the losses were evaluated using this function. The genetic algorithm chose a location based on the parent or parents and based on a fixed DG amount, chosen by the operator, the losses are calculated.

4.5 Model Reductions and Assumptions

The AC model required no presumptions or calculation concerning the load data, line information, and transformer parameters as this data comes all from the existing system. In constructing the DC model, assumptions concerning the DC/DC converter efficiency and DC distribution lines, loads, and source components were necessary and are discussed in the following subsections.

The DC/DC converter model in SKM did not correctly represent a DC/DC converter nor was the set efficiency reflected accurately. The inverter model had similar problems. For these reasons, aggregation of the load and DC/DC and inverter often became necessary. The models implemented for the inverter and DC/DC converter to determine losses and load flow in SKM and Matlab are also discussed.

4.5.1 Three Line DC System

When performing analysis on a three phase AC system, the typical approach is to convert to a single line diagram in which one impedance per phase is examined. However, since DC does not have phases, this cannot be done. Instead two resistances are needed in the model for a two-line DC model as shown in Figure 4.12.

Yet, an additional line exists for the AC system compared to the DC system as discussed in Chapter 3. This additional line could be implemented as a DC negative thereby doubling the transmitted power. Since the center line, considered as the neutral, has no net current passing through, the model can be reduced to that shown in Figure 4.13.

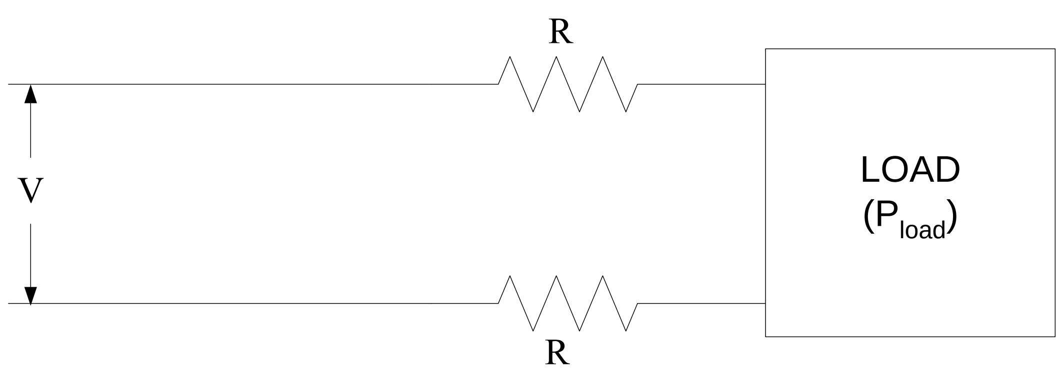


Figure 4.12 DC two-line model.

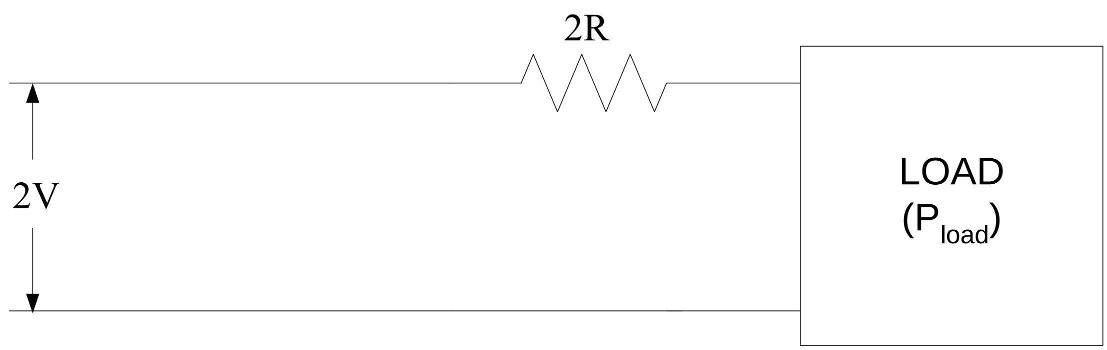


Figure 4.13 DC three-line equivalent model.

The distribution lines employed in the DC model are assumed to be identical to those of the AC model. Hence, the resistance values utilized in the DC model come from the manufacturer specifications of the AC distribution lines. The values used represent the DC resistance of the conductor at a temperature of 25°C.

4.5.2 DC Loads

Since no reactive power is produced or consumed in a DC power system, the loads modeled in DC were assumed to be of the same real power magnitude as that of the AC system. This power value was determined by multiplying the apparent power of the AC load, provided in the original model, by the power factor. Similar approaches have been utilized in other studies [23].

4.5.3 DC Sources

In this analysis, the DC source is assumed to be an aggregation of a DC source and DC/DC converter. This is expected to be a valid representation since the fuel cell requires PEs to regulate the output as discussed in Chapter 3.

4.5.4 DC-DC Converters

As the DC-DC converters are modeled as resistances based on the SKM program, several problems were encountered. First, the resistance calculated is based on two parameters that are not exactly known before load flow is conducted, the voltage and power flow. If these parameters are predicted incorrectly, the efficiency of the DC-DC converter can be inaccurately represented in the model. This was the case during preliminary evaluations. For instance, although the efficiency was input as 97% in SKM the actual resulting efficiency in the model could be as high as 99% or as low as 95%. As such, many of the DC-DC converters were eliminated in the model when the converters were placed directly in front of a load as shown in Figure 4.14. Instead a new load was created such that:

$$P_{new} = P_{in} = \frac{P_{out}}{efficiency} = \frac{P_{old}}{efficiency} \tag{4.50}$$

For those DC-DC converters left in the model, the device ratings were adjusted to ensure that the expected efficiency was correct.

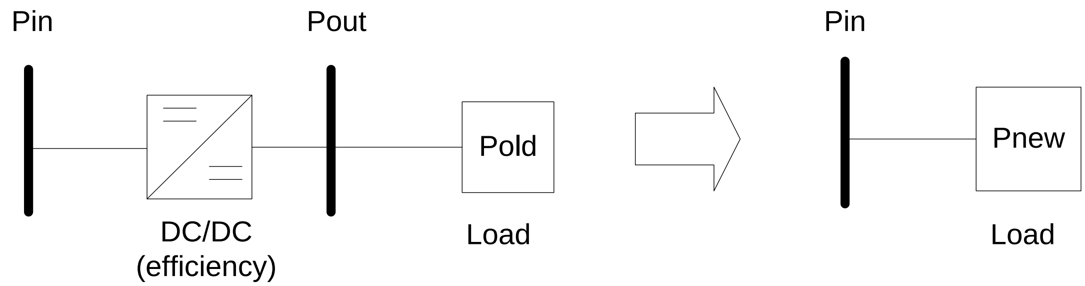


Figure 4.14 Model conversion

In Matlab, all of the DC/DC converters were modeled in this way. As the system modeled is completely radial with no interlocking feeds, this allowed for the distribution system to be dissected into smaller sections. The generation for each portion calculated was reapplied as a load for the higher level system as shown in Figure 4.15. To confirm this methodology, the load flow results and losses were compared to SKM. The differences were less than 1% and can be attributed to the inaccuracies associated with the efficiency of the DC/DC converter model in SKM.

4.5.5 Fixed DC-DC Converter Efficiency

As discussed in Chapter 3, a paralleling topology exists for allowing DC-DC converters placed in parallel to maintain a seemingly fixed efficiency. This topology is assumed to be implemented in this analysis. Hence, the efficiency of the converters is constant and is based on predicted existing technology and future efficiency achievements and not on the loading of the converters.

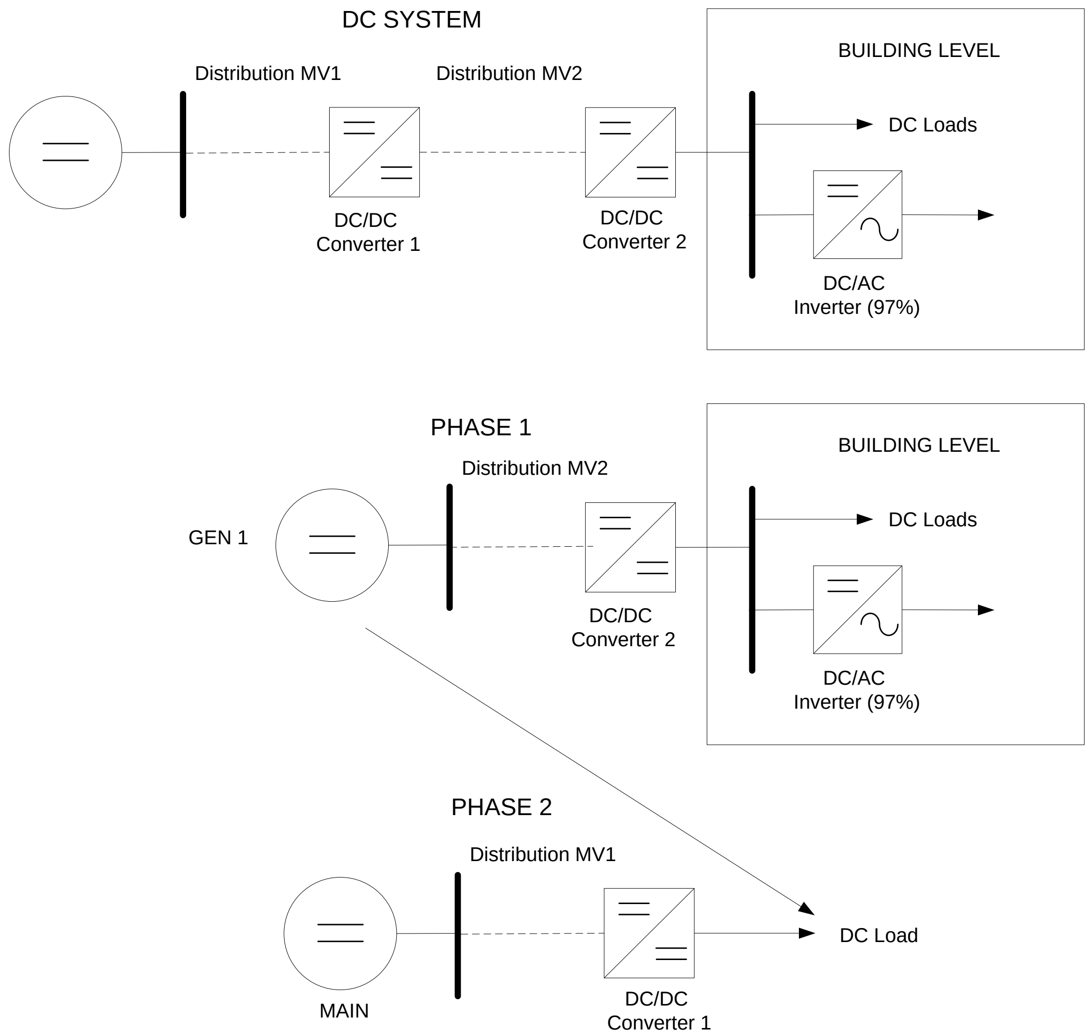


Figure 4.15. DC distribution modeling methods.

4.5.1 Inverter Losses

In constructing both the AC and DC models, inverters and AC/DC converters located near loads were assumed to be constant and were aggregated with the load as discussed in the following subsections. These power converters were assumed to only deliver real power. However, for the systems that required a DC source to deliver AC power to the distribution system, both real and reactive power is necessary. Although the need for reactive power by the distribution system would force higher currents out of the inverter inducing further losses, only the real power was considered. The losses out of the inverter were calculated as follows:

$$P_{loss} = P_{in} - P_{out} = \frac{P_{out}}{.97} - P_{out} \tag{4.51}$$

This is a low estimate of the losses for the converter but is not unbelievable as the reactive power needs were much smaller than the real power requirements for the system studied.

4.5.2 Aggregation of Loads

Since concurrent AC and DC analysis in SKM was not possible, producing models with aggregated AC and DC components became necessary. For the AC system, this resulted in a combining a DC load with an AC/DC converter and an AC load. This is shown Figure 4.16. *P* and *Q* reference the initial load data of the system and %DC indicates the percentage of DC loads. For DC systems, the new load comprised of a DC load along with an AC load supplied by an inverter. This is shown in Figure 4.17.

4.5.3 Calculation of Losses

With all the components modeled, the losses were determined by taking the generation determined by the associated SKM and Matlab and subtracting the original load.

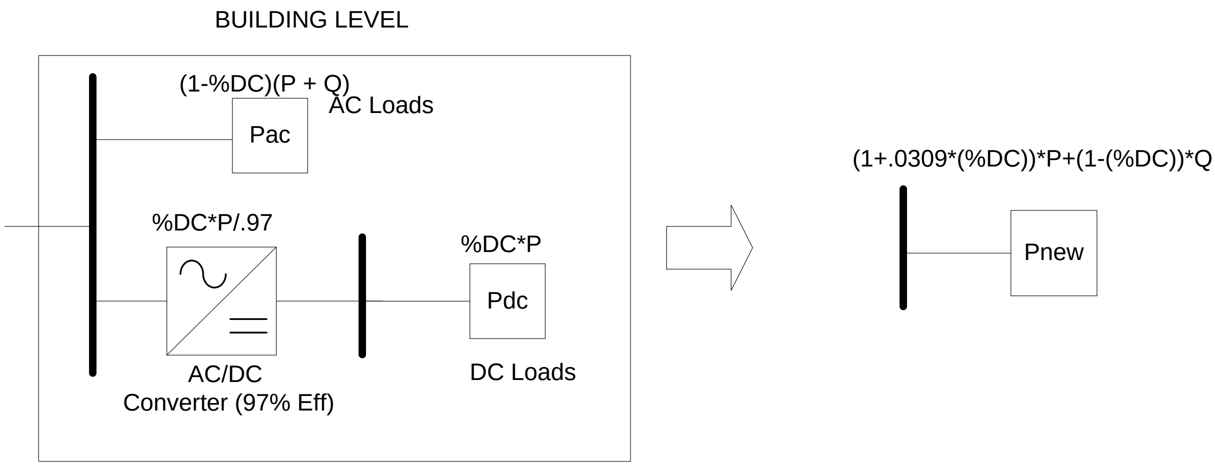


Figure 4.16 Model reduction in AC

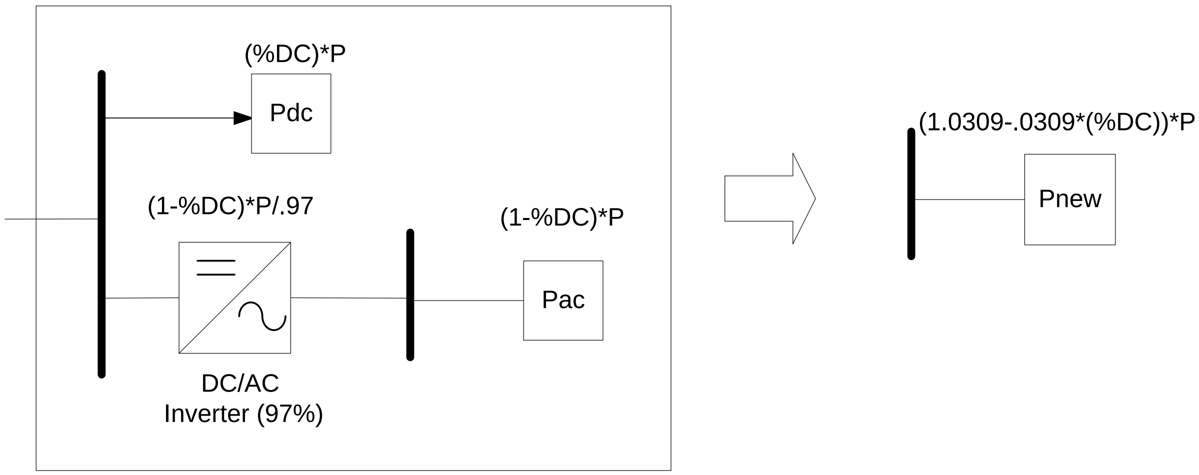


Figure 4.17 Model reduction in DC

4.6 Chapter Summary

The tools necessary to conduct analysis on the power system in question have been discussed. Load flow analysis, loss calculations, and optimum allocation of DG through genetic algorithms are the main focus of this chapter. The software package SKM was also discussed along with the Matlab model and modification necessary to both to accurately represent DC/DC converters and inverters. The next chapter will discuss results of an example systems analyzed in both AC and DC for efficiency and optimum placement of DG in DC.

5 SIMULATION RESULTS

In Chapter 4, the necessary algorithms and equations for load flow analysis in determining net losses and the optimum location of the DG through the genetic algorithm were addressed. This was followed by an examination of the software package SKM, implemented to calculate system losses and assumptions applied to perform the calculations.

In this chapter, using SKM and the Matlab, four different systems (comprised of AC and DC sources, AC and DC distribution components, and AC and DC loads) are formulated and the results of the load flow studies are examined. The AC distribution system was solely modeled in SKM, but the DC distribution system was constructed in both SKM and Matlab. Matlab permitted the results of SKM to be verified while providing more accuracy and versatility. These models were extremely large and elaborate in nature, with several thousand components involved in each model. With the Matlab models GA could also be implemented. This chapter will review these studies.

5.1 Oak Ridge National Laboratory Main Campus Grid

In this study, the ORNL distribution system is under examination. ORNL utilizes a substantial number of facilities stretching over 58 square miles of land with a vast number of electrical loads. The electrical loads range in size from several watts to several hundred kW and come from industrial motors, lighting, computers, air conditioners, and other devices. AC schematics of the ORNL network can be found in Attachement A. Due to the sheer number, the loads are not measured for each device within the building, but instead are measured at the building level. A number of the loads are also high power industrial motors. This results in a power system consisting of over 200 loads or buildings. An abbreviated schematic is shown in Figure 5.1. MV1 and MV2 represent the two different system voltages.

The loads employed have two sets of recorded data, a maximum and an average. During a one-year-span, daily maximum and average building loads of the power system in question were measured. At the end of the year, the daily averages were averaged and the maximum was found for the whole year. The values for the maximum and average of the loads can be located in Attachment B. The AC average and maximum instantaneous power usage for the entire distribution system for the year are 31.9MVA/27.1MW and 42.6MVA/36.2MW, respectively.

The ORNL distribution system is divided into three voltage divisions, two medium voltages(MV) and a low voltage(LV). The MV designations are 13.8kV and 2.4kV while the LV magnitude is dependent on the building loads and is usually 480V, 240V, or 208V.

The components of the model that are implemented in the load flow analysis are the distribution line, transformer, load, and capacitor for Var compensation. These components account for more than 900 components in the model. Buses are also necessary for analysis of the data and are placed in between each load flow component. The total number of buses in the model exceed 700. The fault interruption devices in the model were ignored due to the negligible resistance these devices add to the overall power system.

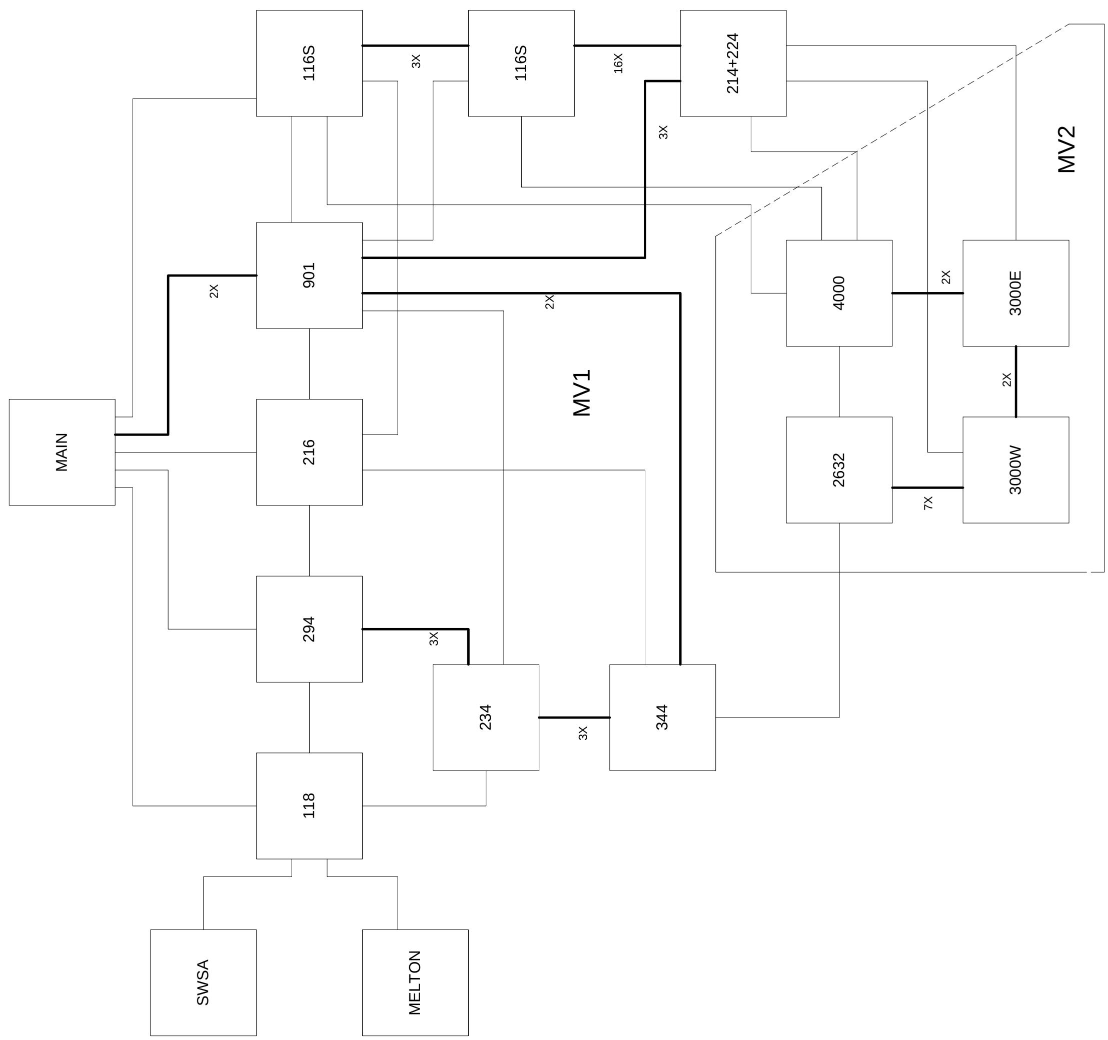


Figure 5.1. Shorthand view of ORNL schematics.

5.2 Loss Comparison (AC vs DC)

For the comparative study, two systems were placed under examination. The first system represented in Figure 5.2A and Figure 5.2C depicts the conventional AC distribution system with an AC source and DC source. Note that a DC source requires an inverter to convert the DC output to AC. The rest of the system is composed of a transformer that lowers the voltage for AC loads and a rectifier to convert the AC voltage to DC. Figure 5.2B and Figure 5.2D show the proposed new DC distribution system. In this system, a DC source either supplies power directly to the distribution system or an AC source must feed a AC/DC converter. The DC system then feeds a DC/DC converter that lowers the voltage for the DC loads and inverts the voltage for AC loads.

5.2.1 Pure DC Systems Versus Pure AC Systems

In this examination, a DC system composed of a DC source, DC distribution system components, and DC loads is compared to an AC source, AC distribution system and AC loads. The AC system model is based on the existing information of the ORNL system while the DC system is developed in relation to this AC model. In the DC model, the efficiency rating of the DC-DC converters were assigned to three different efficiencies, 95%, 97%, and 99.5%. The voltages of the DC system were also varied to represent the I^2R losses. The total losses are provided in kW. The results of a DC system operating at maximum operation is shown in Figure 5.3.

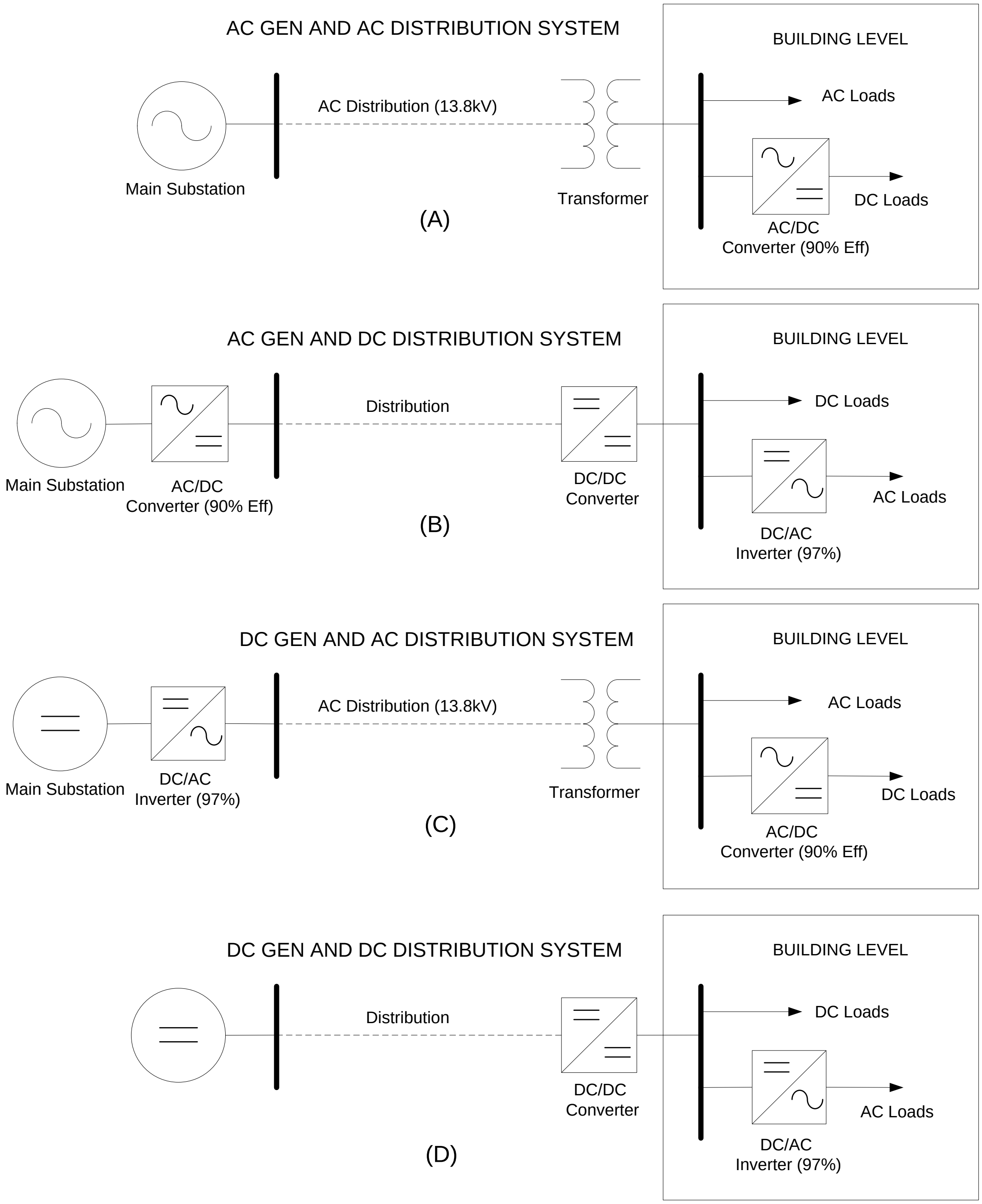


Figure 5.2. System models for comparison

The equivalent AC system only had a loss of 800 kW. Table 5.1 shows the results. Based on a straight comparison of a 100% AC system and a 100% DC system, AC would have fewer losses for DC converter efficiencies operating below 99.5% and with system voltages exceeding 18kV.

When adjusted to the average power, the AC power system again had fewer losses compared to the DC power system when the converter efficiency is again below 99.5% with system voltages higher than 18kV. Figure 5.4 shows the losses of a 100% DC system. The equivalent AC system average system losses were determined to be 412 kW as shown in Table 5.2.

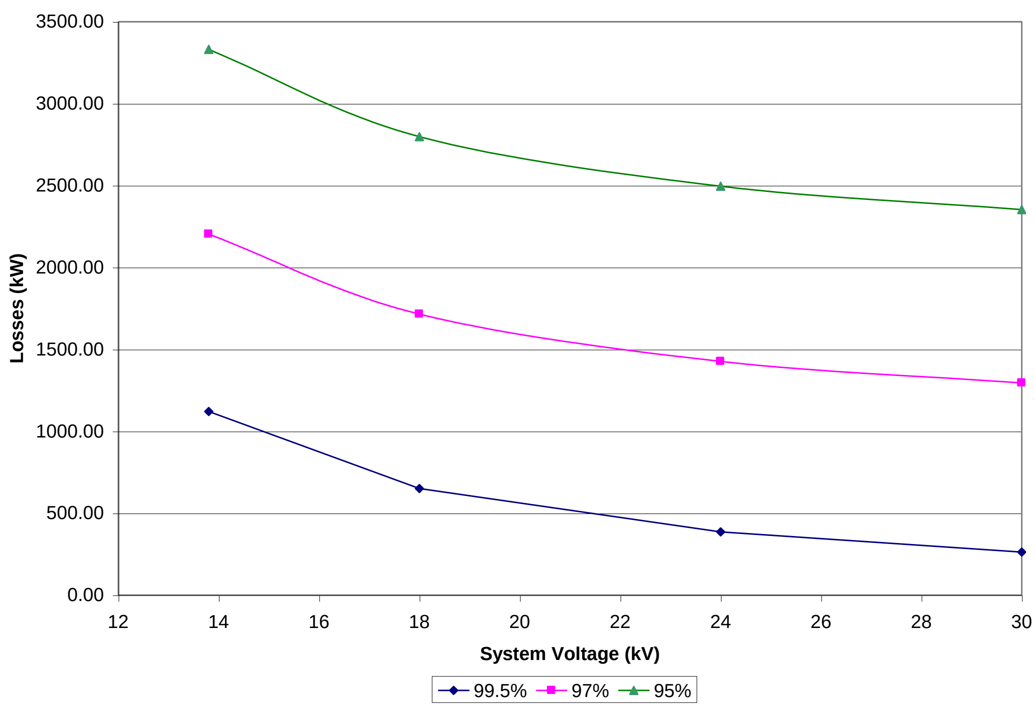


Figure 5.3 DC power system losses for maximum operation.

Table 5.1 Losses (kW) based on maximum loading of pure AC and DC power systems.

System Type	System Voltage			
	13.8kV	18kV	24kV	30kV
AC	800	-	-	-
95%[1] DC	3332	2799	2496	2354
97% [1]DC	2204	1716	1427	1296
99.5%[1] DC	1121	651	386	263

[1]represents DC-DC converter efficiency

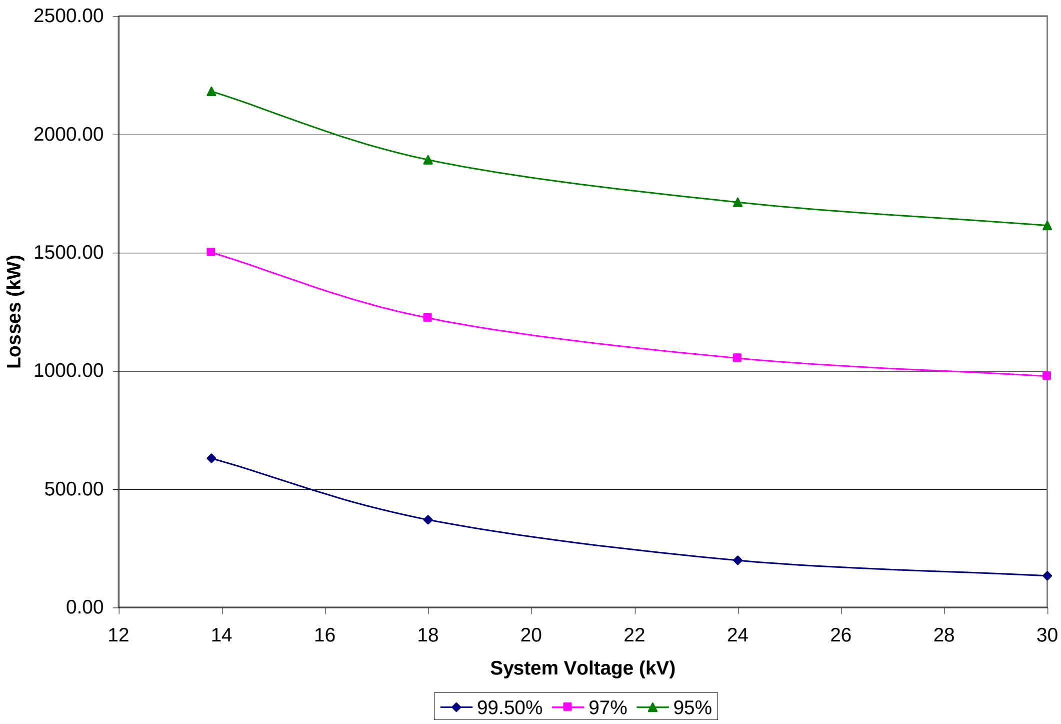


Figure 5.4 DC power system efficiency for average operation.

Table 5.2 Losses (kW) based on average loading of pure AC and DC power systems.

System Type	System Voltage			
	13.8kV	18kV	24kV	30kV
AC	412	-	-	-
95%[1] DC	2181	1892	1712	1614
97% [1]DC	1500	1223	1053	977
99.5%[1] DC	630	370	198	133

[1] represents DC-DC converter efficiency

These results can be anticipated. As suggested in several of the DC studies, most of the losses associated with a power system can be linked to the conversion stages. Although the expectation is that DC would have a higher efficiency in direct transmission, the current converter technology cannot compete with the mature technology of the AC transformer. Therefore, since AC transformers have efficiencies as high as 99%, AC should have the higher efficiency when comparing a 100% AC system to a 100% DC system. For completeness, another evaluation was conducted for a DC distribution system with AC industrial motor loads driven by inverters.

5.2.2 DC System with AC Motors

In this evaluation, the same DC distribution system was utilized except the industrial motors were not converted to DC loads. AC motors are cheaper and more durable than their DC counterparts. As such, losses were again calculated with a DC distribution system containing inverter driven AC motors. These motors were assumed to be completely real power based loads. This time the DC-DC converter efficiencies were varied and the inverter efficiency and DC system voltage were set to 97%, and 30kV respectively. The results are shown in Table 5.3.

Of course, building level systems are not completely driven by one type of load or the other. Instead, generally a mixture of AC and DC loads comprise the overall load of a building. Hence, this raises the question: What about an AC system with DC loads and DC generation and a DC system with AC loads and AC generation?

5.2.3 Mixed Loading

To form a realistic study, the model of the power system should be composed of partial loads of both AC and DC components and be compared with the AC and DC generation. Therefore, a partial loading of the different load types was examined based on the average model data, where the AC system is based on 13.8 kV and the DC system with 30 kV. The AC/DC converter and inverter efficiencies were 97%. These efficiency values are typical of these components in the power system.

Table 5.3 DC distribution losses with AC industrial motor

DC(kW)	DC(kW)	DC(kW)	DC(kW)
90%[1]	95%[1]	97%[1]	99%[1]
3383	1677	1053	460
[1] represents DC-DC converter efficiency			

Table 5.4 and Table 5.5 contains a compilation of the losses for the varying system configurations composed in Figure 5.2. Systems that utilize one type of source and another type of distribution system as is the case with a DC source / AC Distribution system and AC source / DC distribution system had the higher losses. The primary cause of these losses comes from the conversion device at the source. When examining an AC source / AC distribution system and DC source / DC distribution system, the losses are convincingly lower. A graphical representation of the losses in an AC source / DC distribution and DC source / DC distribution is provided in Figure 5.5.

Since the primary focus of this dissertation is the application of a fuel cell, or a DC source, a graphical comparison of a DC source / DC distribution system and DC source / AC distribution system was constructed. This is shown in Figure 5.6. From the graphical representation, there is a clear indication that a DC distribution system could support a reduction in losses if there is a higher percentage of DC loads in the system and the DC/DC converter efficiency is high. DC-DC converters that have efficiencies at 90% and in many cases 95% will not be competitive to AC. As evident, a DC distribution system performance can almost be directly linked to the efficiency of the DC-DC converter technologies.

Table 5.4 DC distribution losses based on partial AC and DC loading of power systems

System Type	DC Distribution							
Source Type	AC				DC			
Loads	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)	(kW)
AC%/DC%	90%[1]	95%[1]	97%[1]	99%[1]	90%[1]	95%[1]	97%[1]	99%[1]
100/0 [2]	5096	3274	2622	2002	4134	2366	1734	1132
50/50 [2]	4718	2913	2278	1650	3767	2016	1400	791
0/100 [2]	4322	2563	1920	1309	3383	1677	1053	460
[1] represents DC-DC converter efficiency [2] represents ratio of AC/DC loads								

Table 5.5 AC distribution losses based on partial AC and DC loading of power systems

System Type	AC Distribution	
Source Type	AC	DC
Loads	(kW)	(kW)
AC%/DC%		
100/0 [2]	412	1273
50/50 [2]	714	1588
0/100 [2]	1074	1974

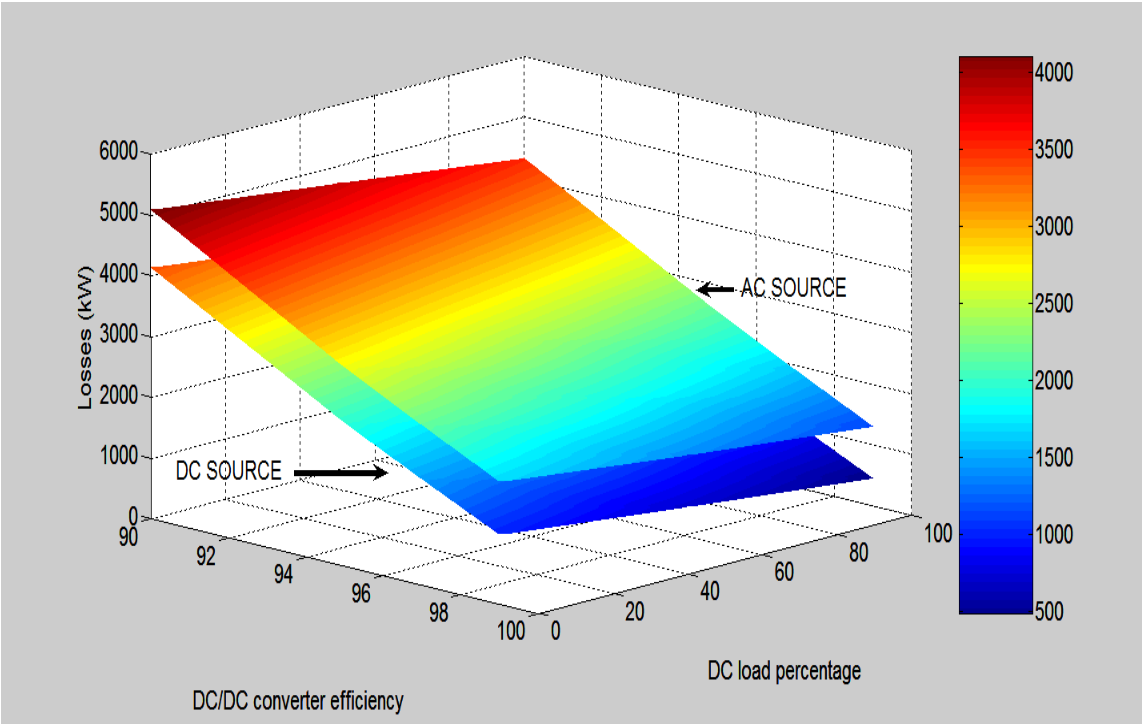


Figure 5.5 DC distribution with mixed loading

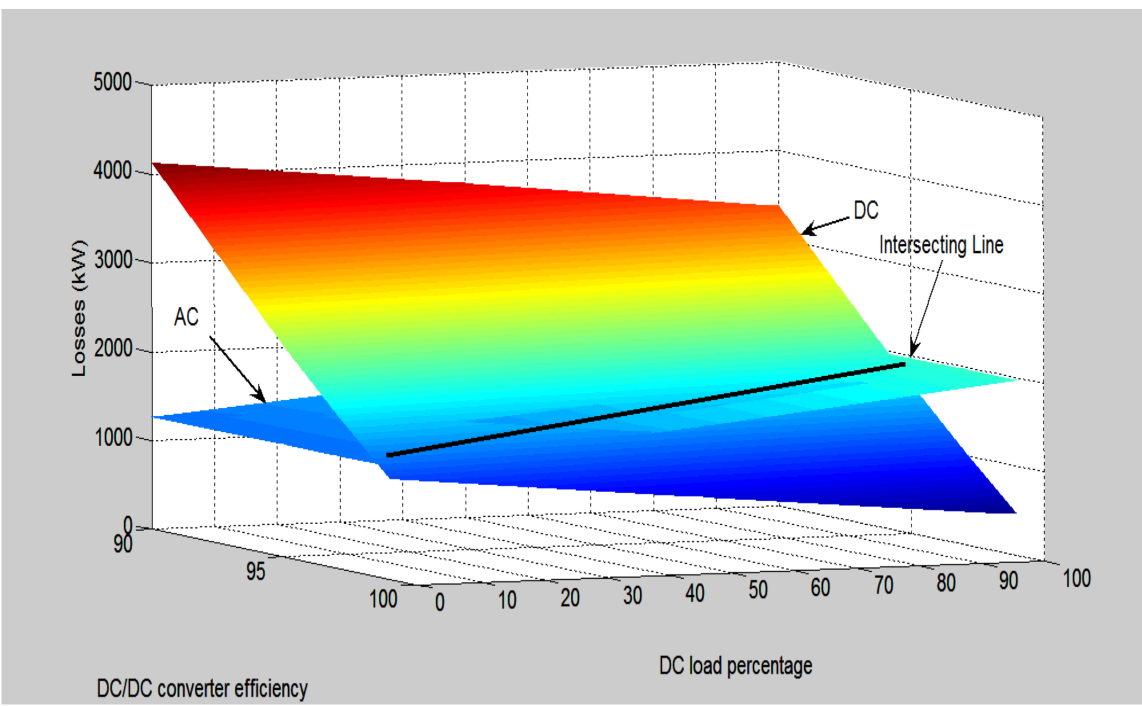


Figure 5.6. DC source, AC and DC distribution systems with mixed loading

5.1 Application of GA

In this study, DG placement consists of applying the genetic algorithm to the DC ORNL distribution scheme and several general DC feeder designs. The genetic algorithm provided a means to calculate optimum locations without utilizing impedance values in the load flow directly. For each system different rules of DG placement were developed.

5.1.1 ORNL Distribution System

The ORNL system was modeled in Matlab and the GA toolbox was utilized to find the optimum locations for DC DG placement. Two fixed amounts of generation were chosen, 50kW and 1MW, and placed optimally throughout the system. The algorithm was implemented in such a way that if the same location was found to optimally suit two DG sources, the DG sources would be added into one. For example, if a 50kW were optimally placed at a location twice, the DG would be made into a 100kW.

When the DC/DC converter was combined with the load signifying that distributed generation could not be located between the DC/DC converter and the load, early testing indicated that minor efficiency gains, a few hundred watts, are achievable with distributed generation. As previously mentioned the DC lines result in minor losses. The conversion devices comprise the most significant portion of the losses.

As a result, the model was adapted in such a way that the fuel cell could be placed between the load and DC-DC converter. In doing this, several constraints were imposed on the placement of the generation sources:

- The DC/DC converters were considered to be unidirectional and therefore limits were imposed to prevent generation sources that exceeded the average load. This also prevents power from flowing in the reverse direction on the feeder. Placement of DG in the feeder system has brought significant attention to the failure of protection devices to sense faults [79-81].
- Subsections of the entire system were created to speed up the placement of dispersed generation and to calculate the losses in the DC/DC converter effectively. The lower voltage subsections were constructed first as power is transferred through two DC/DC converters to reach the loads.

The system losses with the respective DC/DC converter efficiencies are shown in Figure 5.7. Initially as generation sources are added within the distribution system, the

decrease in losses is almost linear. However, once approximately 70 50kW fuel cells have been placed in the distribution system a shift in losses is notable, particularly with the 90% DC/DC converter efficiency. After 70 fuel cells have been placed, a linear decrease in loss once again appears. The following section describes the reasoning behind this transition.

After permitting the genetic algorithm to locate positions in the distribution system for distributed energy optimally, a quick examination demonstrated that the locations resembled a pattern. The genetic algorithm always chose locations between the

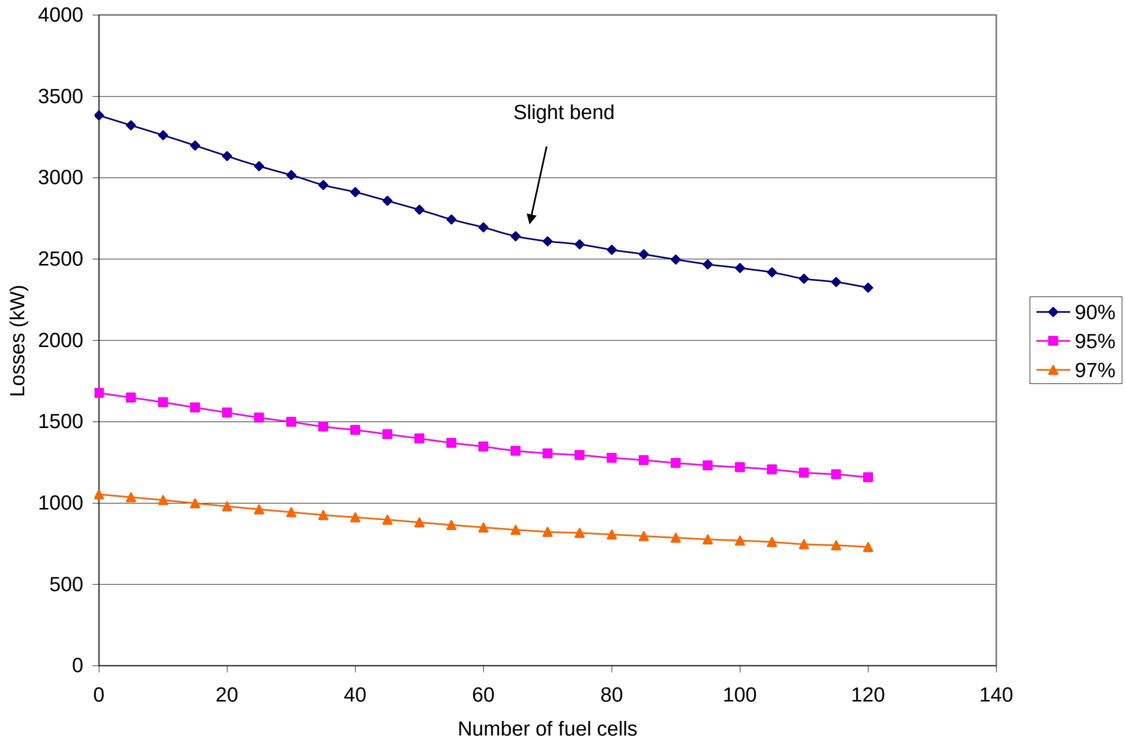


Figure 5.7 Losses with in DC system with the placement of distributed generation

DC/DC converter and load as shown in Figure 5.8. At this location in this model, the generation source delivers power to the load at no loss. As a result, the net savings in energy are derived from the DC/DC converter and line loss.

The above shift in losses comes from the reduction of losses of a set of two DC/DC converters to a single DC/DC converter. Loads within the lower voltage half of the system must have power delivered through two DC/DC converters, while loads in the higher voltage sections have power delivered through a single DC/DC converter. As a result the change in losses from passing power through 2 DC/DC converters is almost ½ of that experienced when passing through one DC/DC converter.

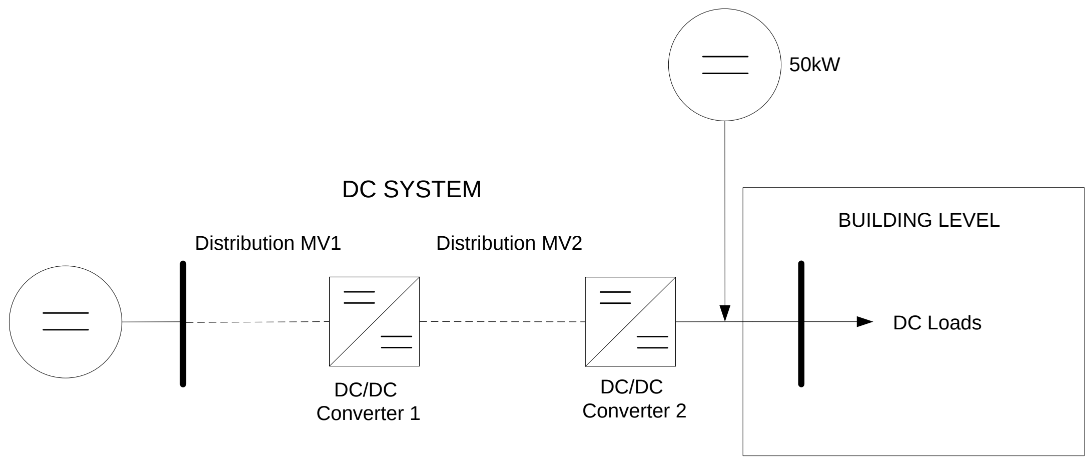


Figure 5.8. DG placement in DC distribution system

5.1.2 General Feeder Examples

To further access the optimum location of a DG source in a DC distribution system and to develop generalizations, three different feeder examples were developed and examined. These are shown in Figure 5.9. The feeder types are based on various load configurations along a feeder. The name "radial increasing load (RIL)" is being provided to a feeder that has an increasing load at each unit distance down the feeder, "radial flat load (RFL)" to a feeder that has an equal load at each unit distance down the feeder, and "radial centered load (RCL)" that has the largest load in the middle of the feeder. The feeder examples are based on a 30 bus systems with DC/DC converters with fixed efficiencies of 95% feeding various load sizes. The total load for each feeder is 750kW and the line resistances are based on 300ft, 336 aluminum cable sections. The main source of generation for the example feeders is assumed to be a generator connected to

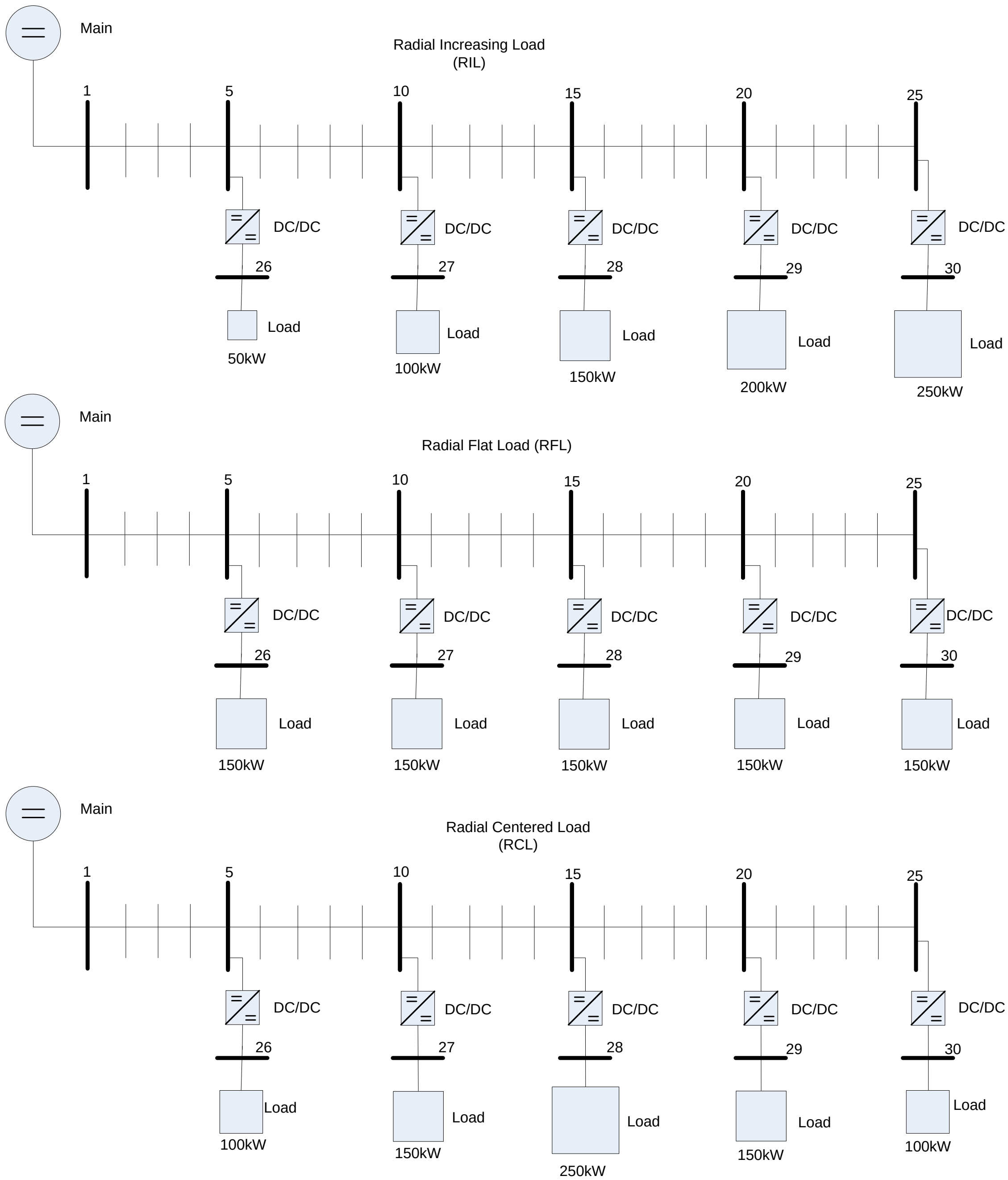


Figure 5.9. Example feeders

bus 1 that represents power coming from a main substation. In this case, the DC/DC converters are considered to be bi-directional (power can flow in both directions).

In assessing the optimum location for DG for the three systems, the genetic algorithm was implemented for a range of DG sizes. The results are shown in Figure 5.10 (losses) and Figure 5.11(optimum feeder location.) The DG size was limited, graphically, to 500kW for RIL and RCL and 310kW for RFL. Increasing the DG beyond these sizes resulted in losses that approached a system without DG.

The results of this analysis led to the development of basic guidelines for placement of DG optimally in a DC system. The guidelines are as follows:

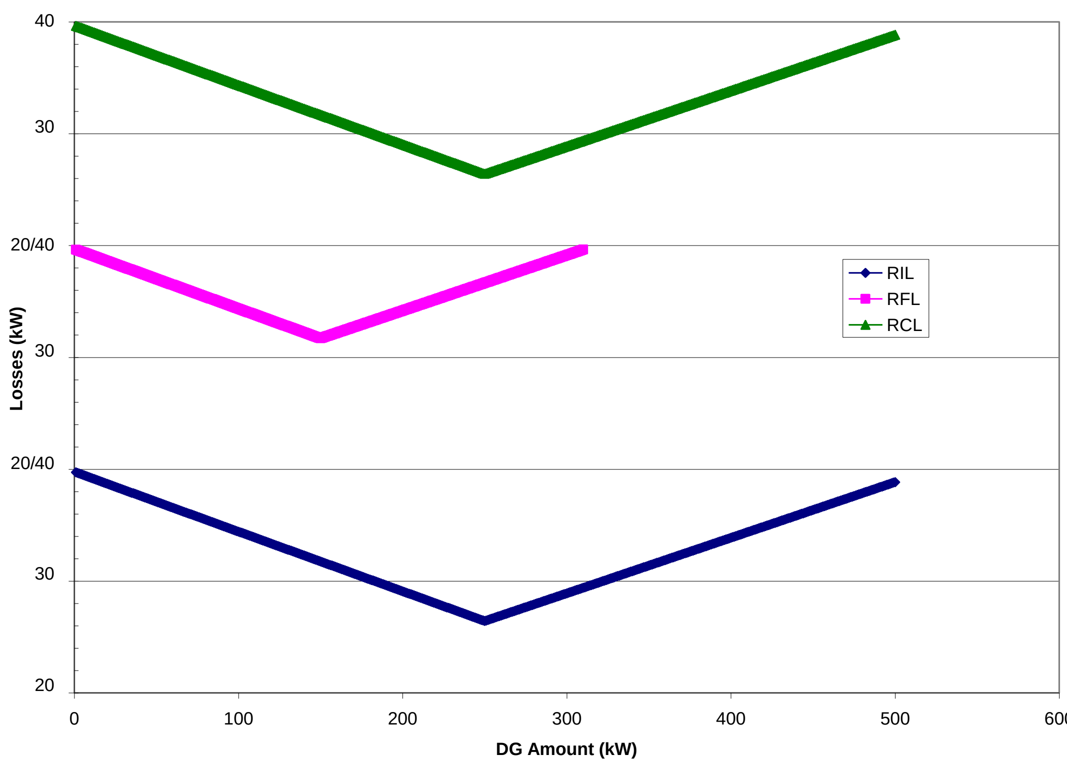


Figure 5.10 Losses for various feeder types

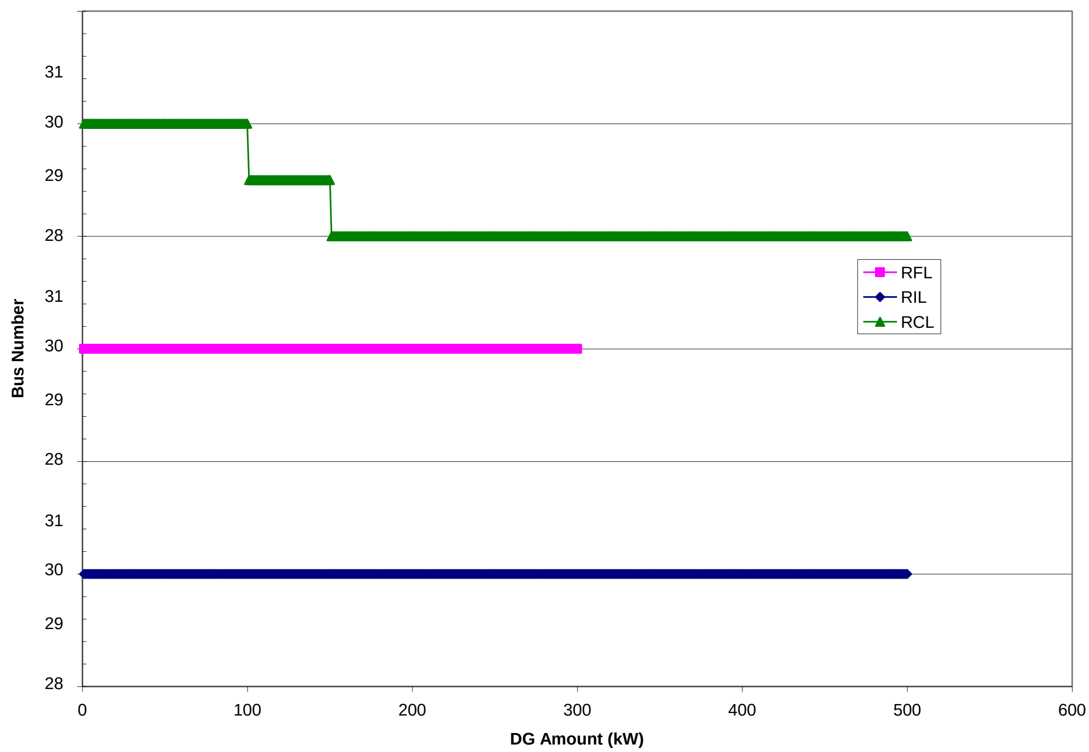


Figure 5.11 Bus number for optimum location on various feeders

- **Placing a DG source directly at the load locations provides the lowest losses**. As shown on Figure 5.11, the optimum bus location for all cases is between Bus 28 and Bus 30 (all buses between Bus 26 and Bus 30 are linked directly to the load.) Through directly delivering power from the DG source to the load, thereby having no assumed losses, losses are reduced in the overall system.
- **Matching the load directly with a DG source at the location of the load, reduces losses compared to the over-sizing and under-sizing the DG**. Examining Figure 5.10, the lowest losses occurred when the DG matched the load. When the DG is below the size of the load, the remaining needed power must be delivered from the main substation, down the feeder, through a DC/DC

converter to reach the load. This results in significant losses from the DC/DC conversion stage. For a DG greater than the load, the DG feeds power back through the local DC/DC to the feeder and than through another DC/DC converter to an adjacent load. Again, significant losses arise from the DC/DC converter stages, but with two stages instead of one.

- **The optimum location for DG placement is dependent on the amount of DG, but in general will be at the load near the end of the feeder.** The results for RFL and RIL cases show that independent of the amount of DG, the optimum location was always at the load bus at the end of the feeder. The RCL case provided for the development of a more complicated "rule of thumb."

  If the designer can choose the amount of DG, the largest available load is the proper amount and location. However, if multiple loads are present with similar sizes or the DG size cannot be chosen, than the methodology developed in Figure 5.12 should be applied. Assuming that the DG size chosen is below the maximum size of all the loads in the feeder, the best approach is to start at the end of the feeder, compare the DG size to the load, and move up the feeder towards the main substation. If at time during this process the DG size is below the load, the optimal location for DG placement has been found. This does not have to be the largest load.

  The visual depiction of Figure 5.13 describes why. Placing the DG at the end of the feeder, or as close to the end as possible, allows for a portion of the feeder to carry no current. Other studies neglected the losses associated with the voltage

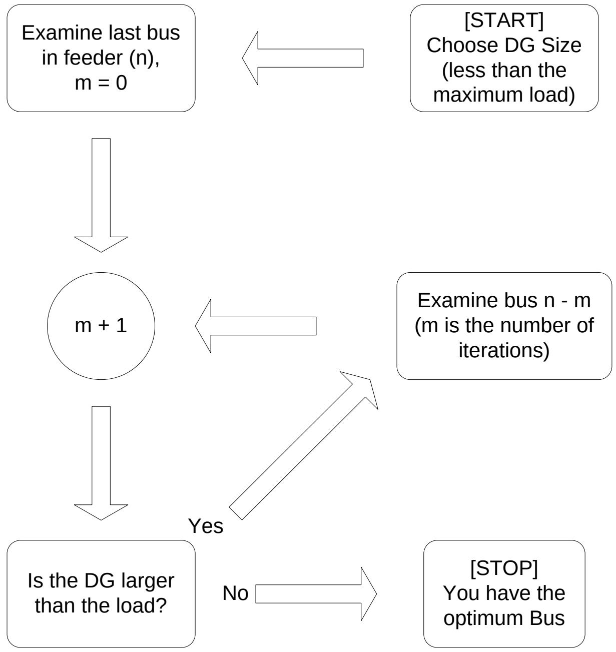


Figure 5.12. Method for locating optimum location based on DG size.

conversion stages and therefore assumed values of DG could feed most or all of the feeder without compromising losses. However, for the cases examined, when the DG exceeds the local load the losses grow significantly and more than make up the line losses.

- **Benefits are still achievable with increasing DG size beyond local load as long as the DG size does not exceed approximately twice the local load.** For each of the cases examined, the losses improved when the applied DG size was below twice the load supplied. Examining the RIL case, a 500kW DG unit would feed the 250kW local load, but must deliver 250kW through the local DC/DC converter and than through another set of DC/DC converters to adjacent loads.

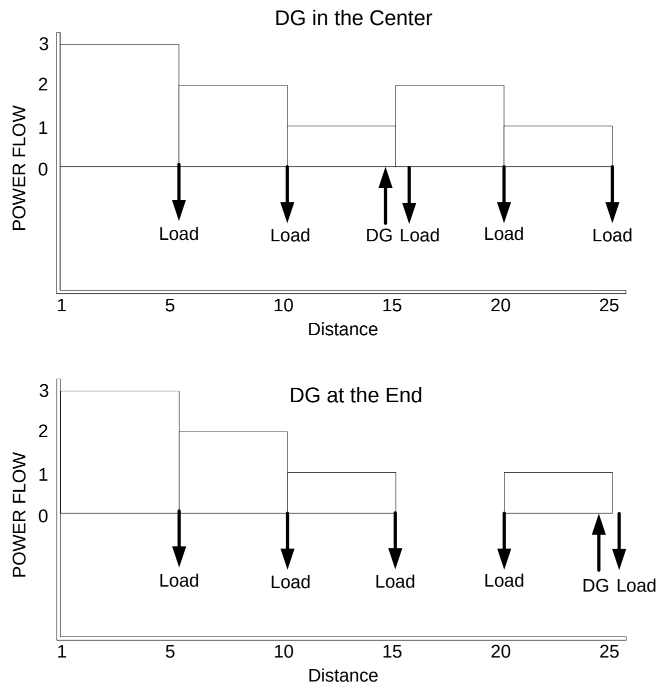


Figure 5.13 Loss depiction of DG in center versus DG at end

Hence the 250kW has two stages of losses. This does not save significantly from a system with a 500kW DG unit placed on the feeder as shown in Figure 5.14 since the 500kW source must only pass through a single stage of DC/DC converters.

5.1.3 Designing System Based on Forecast

Another factor that is often not considered is the growth of nearby loads and how this affects the placement of the DG based on the criteria provided in the previous section. Using the example cases derived in the previous section, evaluations relating the effect of an increase in load on a non-optimum bus were conducted. The following results are examined based on interest:

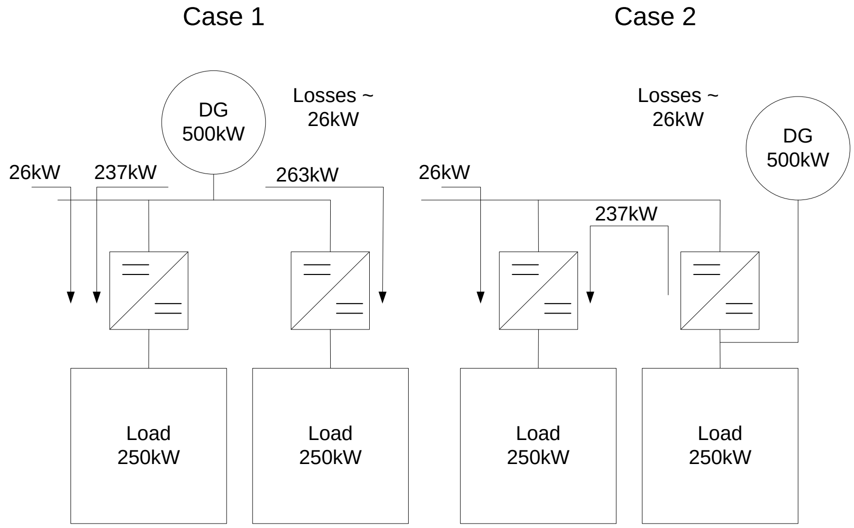


Figure 5.14 Demonstration of equivalence in DG placement.

- Envelopes for the change in optimum location and necessary additional loading were generated for the three example systems, RFL, RCL and RIL.
- The deviation in losses between the initial optimum and worst case locations in relation to load growth for the three cases were evaluated.

5.1.3.1 Optimum Location Envelopes

Areas, or envelopes, for the optimum location of DG with increased loading were developed to provide insight into the sensitivity with respect to the change in load and amount of DG. For these case scenarios, the load at a particular bus and only that bus was incremented by 1kW.

For the RIL case, bus 30 was originally the optimum bus for DG and remains the optimum choice until a load on another bus exceeds 250kW and the DG generates above 250kW as shown in Figure 5.15. Once this load and DG grow beyond 250kW, the newly loaded bus becomes the optimum. In this case, this requires the loads to grow by the percentages depicted in Figure 5.16. In particular, the necessary load growth for bus 26 to become optimum is over 400% and is much greater (based on percentage) than that for the other buses. This is due to the bus having originally the smallest load. This feeder type permits significant load growth in the other buses before the optimum changes.

A similar graphical result is obtained for the RFL case. The optimum location is bus 30 as long as the load on any other bus and DG does not exceed 150kW as shown in Figure 5.17. In this case, however, the necessary load growth for a change in optimum is small and reflects the sensitivity of this type of feeder to a change in load as shown in

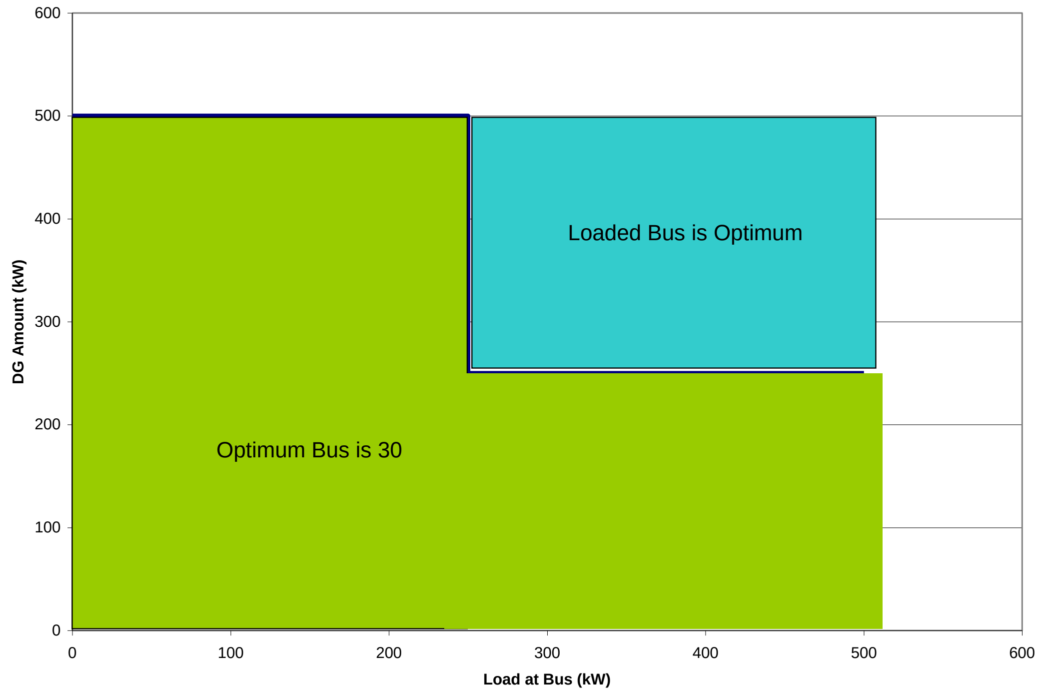


Figure 5.15. Results of DG placement for RIL

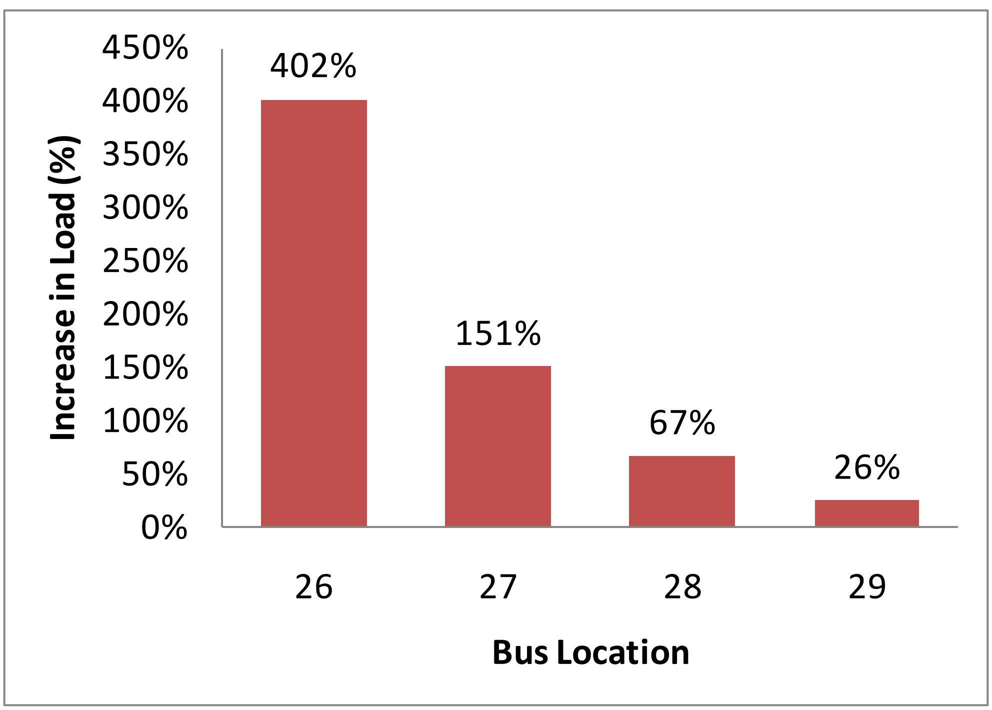


Figure 5.16. Increase in load for bus to become more optimum with DG greater than 250kW.

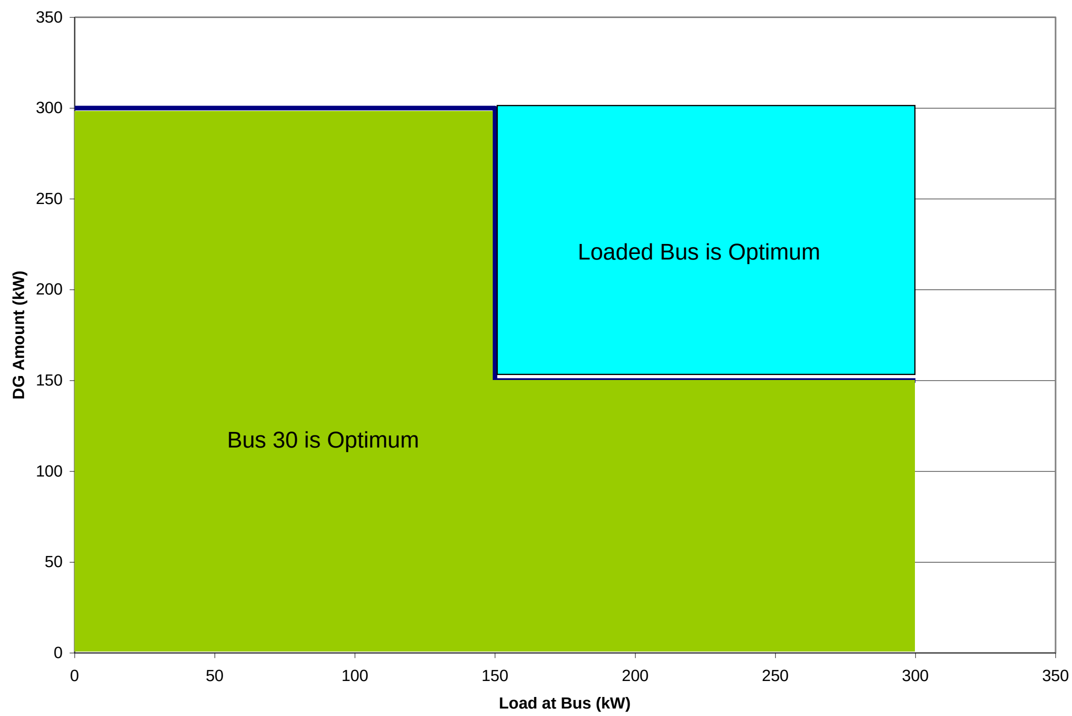


Figure 5.17. Results of DG placement for RFL

Figure 5.18. With this feeder type, a growth of a single kW will result in a change in the optimum location.

The RCL case had identical results to that of the RIL case in terms of the optimum bus locations with the exception that the original optimum bus is 28 instead of bus 30. The percent of load increase for each bus that was not optimum is provided in Figure 5.19. This type of feeder permits significant growth of nearby loads as well before a change in optimum location occurs.

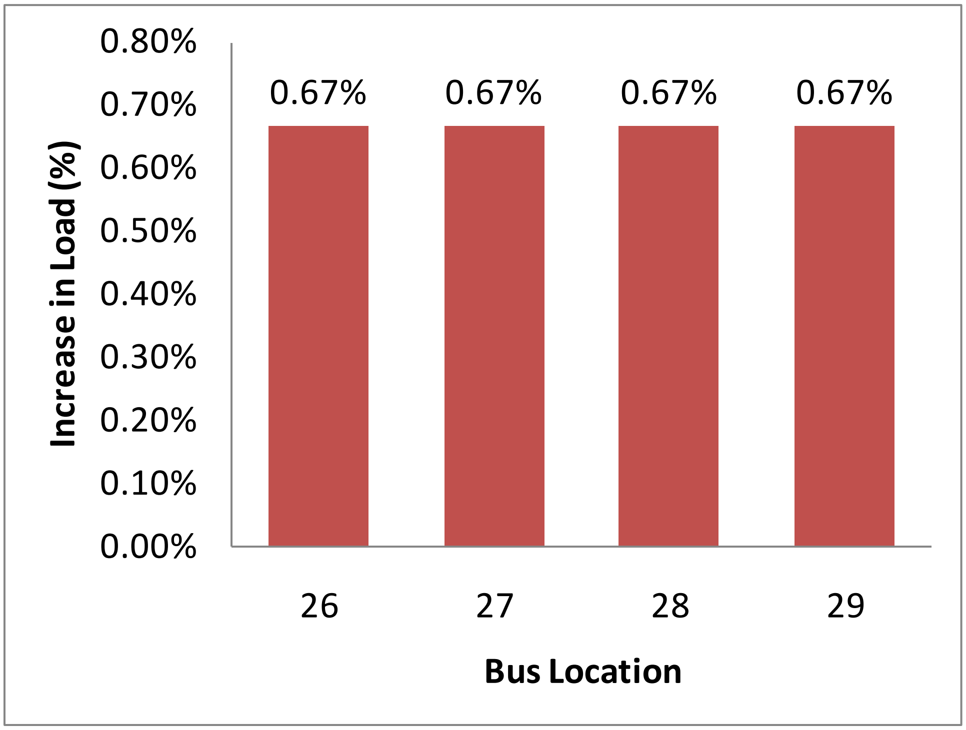


Figure 5.18. Increase in load for bus to become more optimum with DG greater than 151kW.

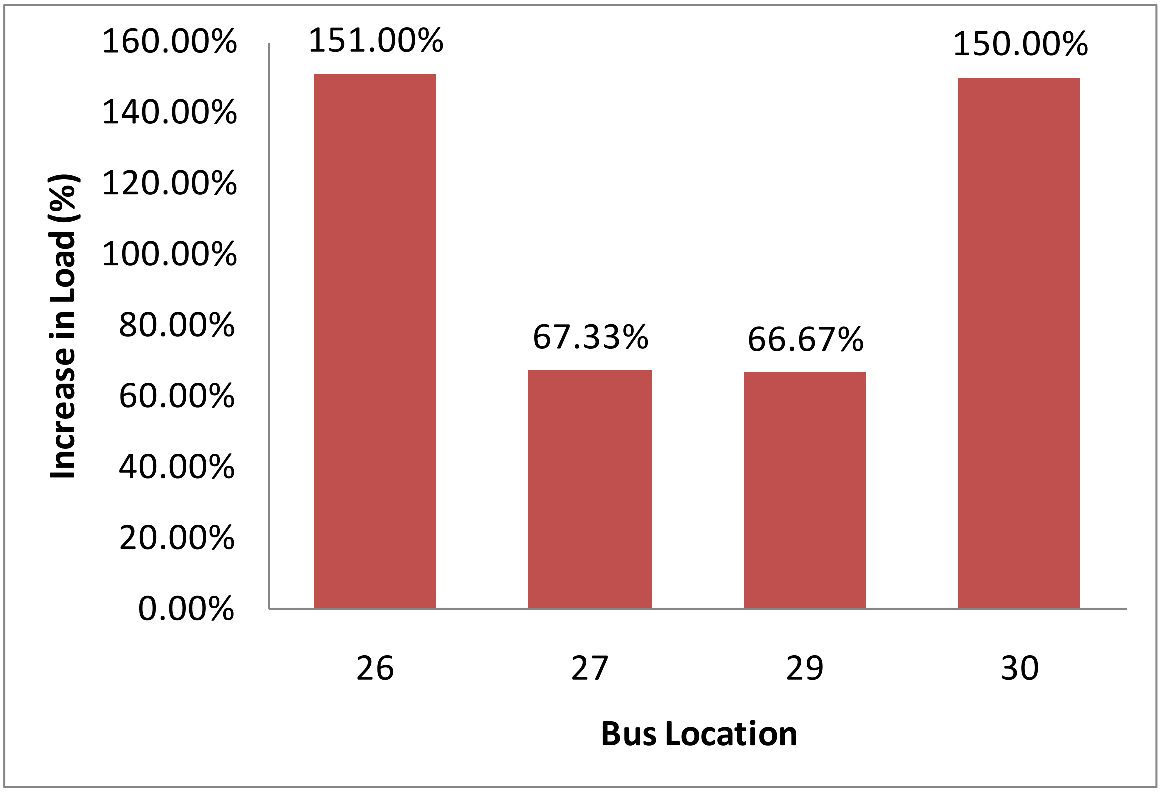


Figure 5.19 Increase in load for bus to become more optimum with DG greater than 250kW.

5.1.3.2 Loss Deviations in Relation to Loss Increases

An incorrect forecast on the load growth at any particular bus can effect the optimum placement of DG and increase the corresponding losses from the minimum achievable. In this case, the load at the bus with the worst losses (bus 26) was increased, and a new optimum was located, and compared to the previously chosen optimum in terms of losses for each example case.

The results are shown in Figure 5.20, Figure 5.21, and Figure 5.22. A distinct pattern is noted for each case. A steep incline with a sharp transition and decline represents the characteristic curvature for percent loss change in respect to the load growth for each of the feeder types. The steep incline can be associated with the losses of

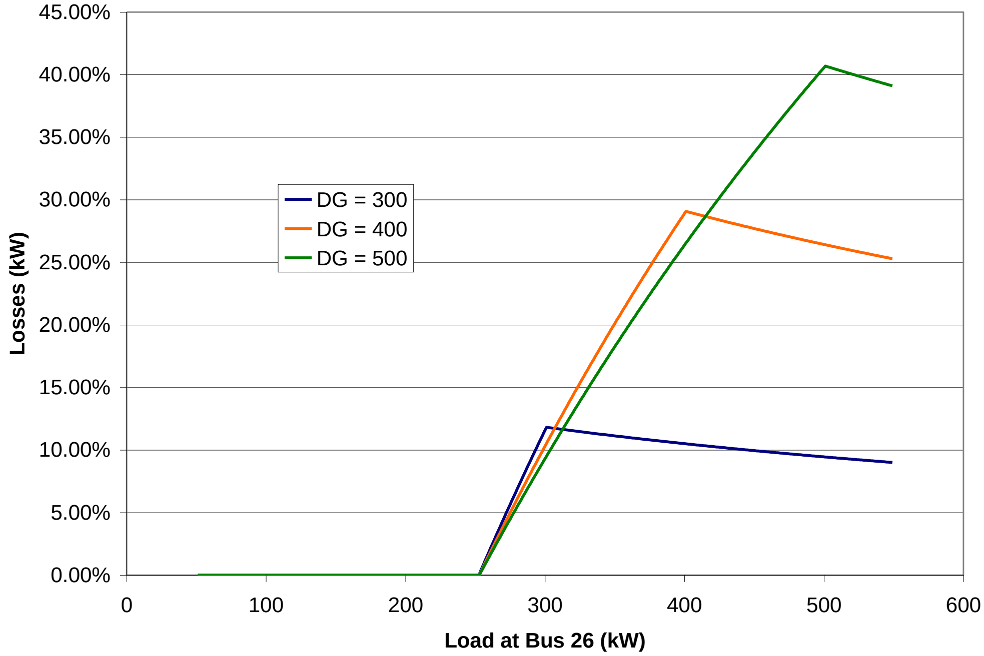


Figure 5.20 RIL sensitivity towards increased loading at bus 26.

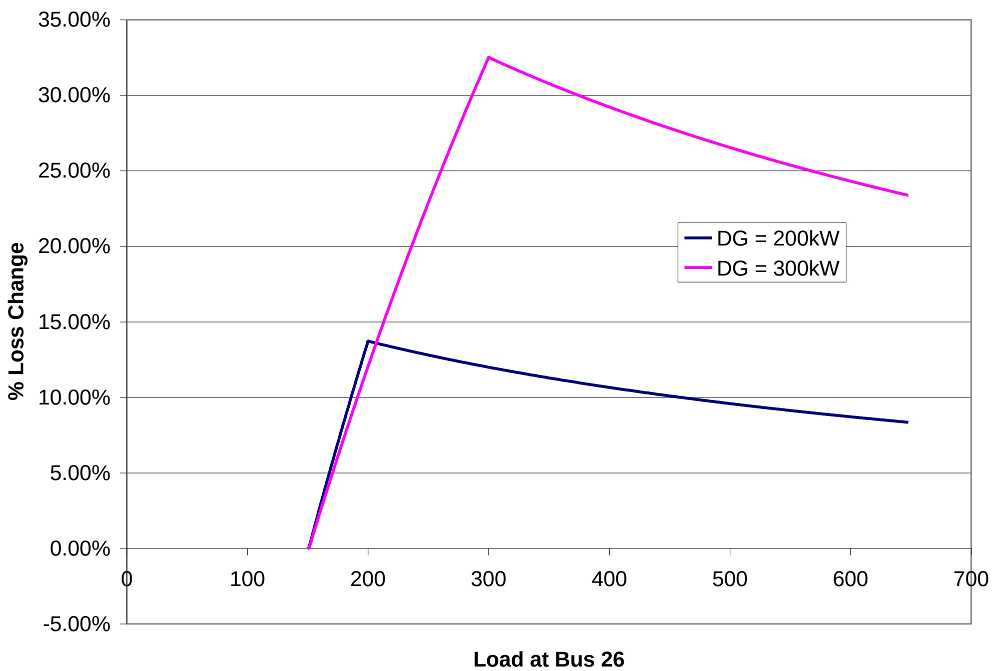


Figure 5.21. RFL sensitivity towards increased loading at bus 26.

the non-optimum placed DG supplying the growing load through two sets of DC/DC converters compared to simply applying the DG (optimally) directly at the load. Once the load surpasses the amount of DG, the feeder must supply the loads in both the optimum and non-optimum cases. As a result, both sets of losses are correlated to a single set of DC/DC converters and the difference is based on line losses which are minor compared to the growth in load. This is the explanation behind the decreasing loss percentage.

The results demonstrate that improper placement of DG can do significant harm in terms of losses, but will have a decreased impact over time as the overall load grows. Furthermore, the higher value of DG placed in the system will result in more risk of higher losses from an incorrect placement.

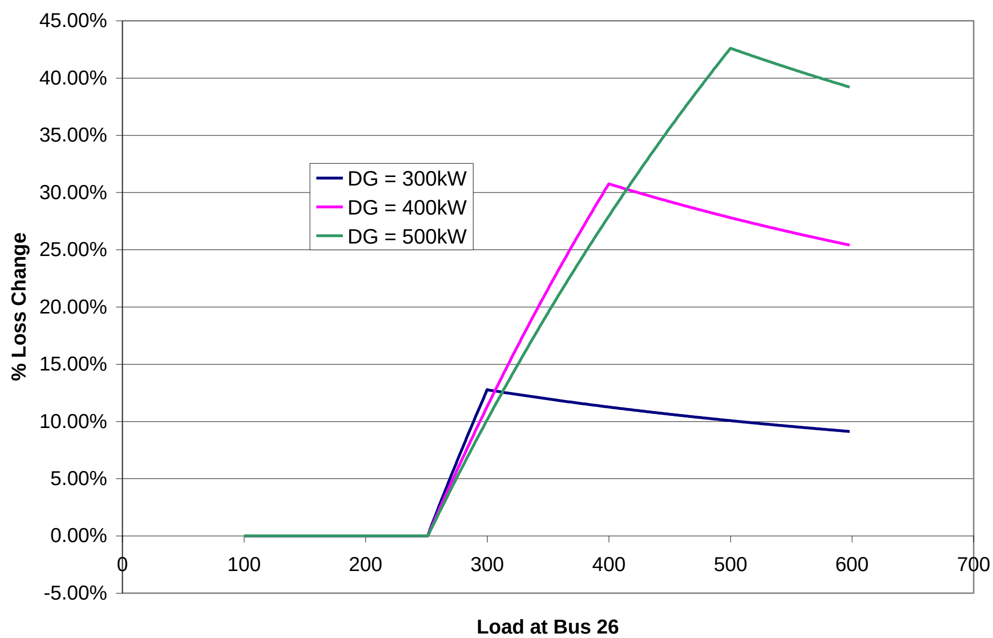


Figure 5.22. RCL sensitivity towards increased loading at bus 26.

5.2 Economic Comparison

As is the case with many projects, economics are the driving factor that determine the success or failure of a concept. In this section, a monetary comparison of AC and DC components is conducted. Components examined are the conversion technologies fault protection technologies.

5.2.1 Transformers and DC/DC Conversion

Semiconductor technologies have come a long way since their invention. Device ratings have increased and the cost of the technology has fallen. Still, the advancement of semiconductors for power electronic conversion devices has yet reached the cost competitiveness of the basic transformer when high power and medium voltage levels are examined. Various vendors for high powered, medium voltage level power electronics and transformers were contacted and cost estimates for these devices were obtained. The cost estimates are based on two different technologies:

1. Oil cooled transformers that utilize new environmentally friendly oils.
2. DC power supplies.

Currently, manufacturers of power electronic devices do not have the market for high powered, medium voltage DC/DC conversion technologies. As a result, direct cost estimates for DC/DC conversion technologies were not obtainable. However, a DC power supply has many components that would be utilized in DC/DC conversion technology.

As shown in Figure 5.23 the cost of the power electronic device technology is more than a factor 10 higher than the conventional transformer. A 150kW DC supply has a price tag greater than $50k, while for nearly the same price a 2500kVA transformer can be obtained. The primary driving factors for this difference are the maturity of the transformer and the current market for power electronics conversion devices.

Transformers have been manufactured for decades with technology advancements mainly focused on the application of cooling and conductor technologies. High powered semiconductor and power electronic conversion devices, on the other hand, are continually advancing with new basic switch designs, material compositions, switching algorithms, and converter designs. Unfortunately, reliability questions still falter significant application and thereby reducing production rates and increasing costs. As the technology continues to advance and more power electronics are incorporated into everyday power system applications, prices will fall make power electronics more competitive. However, at this time, the cost for a DC/DC conversion technology is significantly higher than that of the transformer.

5.2.2 Fault Protection

As noted in Chapter 3, many fault interruption devices are not suited for DC application. Those devices that have DC interruption capability often have a lower rating of interruption capacity. The resulting implication is a higher cost for DC interruption capacity utilizing those AC components that are viable for DC interruption.

Several interruption topologies were also presented which incorporated AC technologies with additional components or utilizing power electronics. These technologies are state of the art and as a result will largely be more expensive.

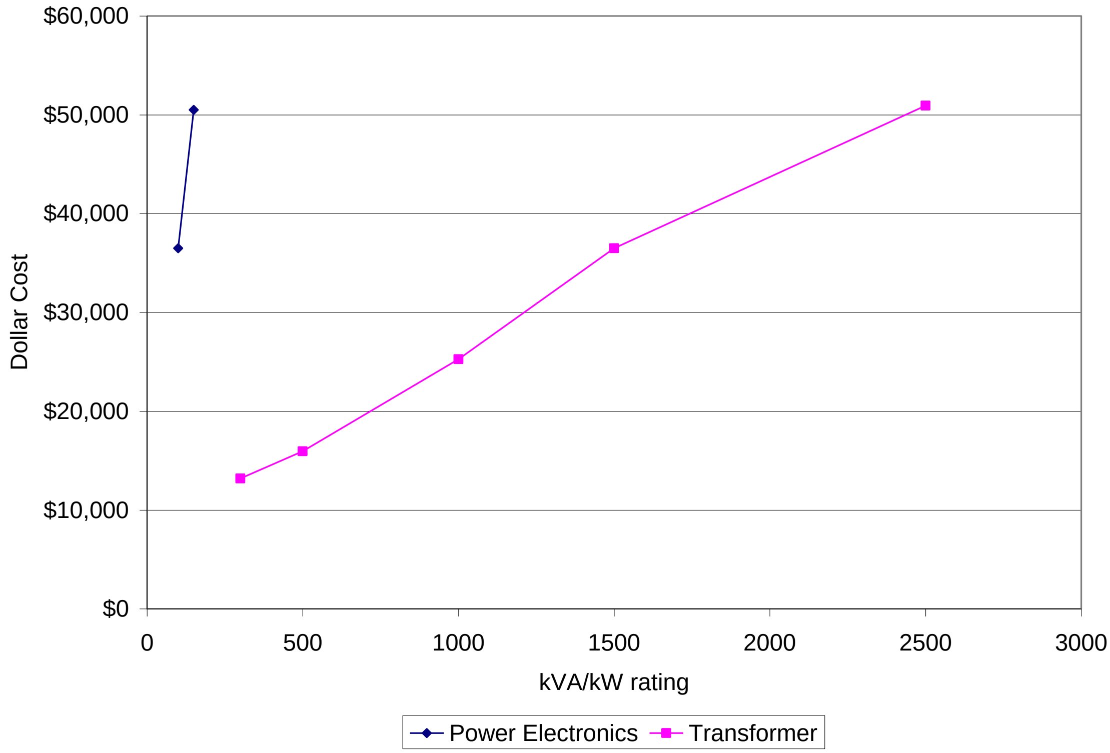


Figure 5.23. General pricing information for transformer sizes [83]

5.3 Chapter Summary

In the work conducted, DC distribution has a potential to provide energy savings when a DC source such as a fuel cell is implemented and the loads are primarily DC. However, the efficiency of the DC/DC converter must be significantly high to make an impact.

Unlike many other DC studies, this study modeled an actual system. This system was extremely large and should depict a typical distribution system. Furthermore, this study evaluated both AC and DC source driven distribution systems and considered the possibility of both AC and DC loads. This is not done in most studies. Last, this study considered the distribution system and was not focused on low voltage (internal to a building) or HVDC systems (transmission).

As discovered, placement of fuel cells in a DC distribution system demonstrates that a significant reduction in losses can be achieved when fuel cells are located within direct proximity of the load. Conceptually the ideal interconnection point for distributed generation is directly to the building.

No other study has performed any type of optimization for DG placement in DC. Other studies conducted in AC have shown that DG placement could be anywhere along a feeder in an AC system. This is due to the reactive power needs and the efficiency of the transformer. This study has demonstrated that DG sources in a DC system are more optimally located near the load and should be more directly fitted to the size of the load. Improper placement of a DG unit can lead to significant losses. However, with significant load growth these losses have a reduced impact.

6 CONCLUSION

At the time of this dissertation, DC distribution does not appear to be have beneficial results when discussing efficiency and cost. The efficiency of a DC system is not as high as that of AC unless the efficiency of the DC/DC converter is within proximity of the industrial transformer. Currently, the market does not support such a device. Line losses appear to be dwarfed by the conversion stage losses and the associated benefits of DC in cable losses are masked. Even when only DC renewable generators and DC loads are in a network, an efficiency of 95% for the DC/DC conversion stages is necessary to be competitive.

Another barrier is that the efficiency of power electronic conversion devices tends to swing based on rating as well. A design that incorporates the parallel operation of power electronics technologies, presented in this dissertation, is key in maintaining a high efficiency for these devices. Future advancements could further increase the efficiency of these devices through new control strategies, material enhancements, and converter designs, but to-date the current vision of DC/DC conversion technologies is that these devices do not have acceptable efficiency levels.

Inserting DC distributed generation can increase the efficiency of a system under question, but optimization of the location is necessary to obtain the least amount of losses. The most efficient location for DG placement is directly at the load bus, assuming the DG size does not exceed twice the load. As shown in this dissertation, properly sizing the DG is important as well. When the DG source is made larger or smaller than the load, extra losses are added to the system due to the DC/DC conversion stages and remove the benefit of placing the DG near the load.

In the case of a fuel cell applied as the DG, the ideal control for the fuel cell should be load following instead of fixed output. This provides the DG the capability to more closely match the load and thereby reduce losses. However, since fuel cells cannot perform a step change, an energy storage system should also be considered depending on the behavior of the load and the size of the step.

As loads grow, the optimum has the potential to change when the DG originally sited is larger in size than the local load. The larger the size of the DG unit placed in excess of the local load, the higher the loss risk will be when an incorrect location is chosen. Nevertheless, even when a significant difference in the percent of losses is obtained due to improper placement, the continued growth of the loads will decrease the apparent percentage of losses.

The associated cost of power electronic devices are also damaging to the potential application of a DC distribution system. Currently, power electronics, even the large scale DC power supply, has a cost that is a multiplier higher than the conventional transformer and AC technology. A foreseeable driving factor that could possibly change this factor is the cost of metals such as copper increasing while the cost of silicon based materials decrease.

Furthermore, a complete change in much of the power system infrastructure would be necessary for conversion to a system that could support DC. Protection, conversion technologies, and many other components would need to be exchanged in order to support a DC system. This can cost on the order of millions for a system.

To summarize, it is the view of this author that a DC distribution is hard to support economically and/or through efficiency criteria based on the results obtained in the analysis and current technologies. Still, technology advancements and new innovations in power electronics could change the view of this author in the future.

6.1 Main Contributions

- A survey of DC distribution technologies, including efficiency comparisons, cost comparisons, and reliability.
- A survey of various optimization techniques for placement of distributed generation.
- Discussed the differences in AC and DC fault interruption technologies and methods for DC interruption
- Discussed DC/DC conversion technologies and a paralleling strategies for more efficient operation
- Derived DC equations for load flow analysis using Newton Raphson Method
- Constructed DC model in SKM to estimate losses for a DC distribution system at Oak Ridge National Laboratory
- Constructed DC in Matlab to estimate losses for a DC distribution system at Oak Ridge National Laboratory
- Calculated losses for multiple case senarios including a AC source with DC distribution system and mixed loading, AC source with AC

distribution system and mixed loading, DC source with DC distribution system and mixed loading, and a DC source with AC distribution system and mixed loading.

- Adopted genetic algorithm to locate optimum bus location based on losses for a DC system.
- Applied algorithm to find optimum locations for distributed generation at Oak Ridge National Laboratory based on a 50kW fuel cell. Conducted a range of 1 to 120 fuel cells within the ORNL distribution system.
- Performed sensitivity analysis on the optimum location of distributed generation and developed a "rule of thumb" for DG placement in a DC distribution system.
- Developed an economic comparison of AC and DC technologies including power conversion technologies and fault protection.

6.2 Recommended Future Work

Although DC distribution at this point in time does not appear to be more efficient or economical based on the technology, further research is still warranted due to possible changes in DC/DC conversion technologies that could lead to a DC system being advantageous. The suggestions of this author include:

- Development of a transient DC model for study.
- Development of short-circuit analysis in DC.
- Development of new DC/DC conversion technologies to increase efficiency.

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7 APPENDIX E (CODE FOR DG PLACEMENT USING GA)

```
clear all;
clc;

tic
%%%%%%%%%%%%% SYSTEM PROFILE  %%%%%%%%%

%%%%%%%%%%% System Parameters %%%%%%%%%%%

global buses;
global swing_bus;
global Pbase;
global Pload;
global P_locations;
global eff;
global exclude;
global gen_max;
global Y;

swing_bus = 12;
buses = 275;
eff = 0.99;
gen_max = 50;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

%%%% Main Substation %%%%
R(1,2) = .0822*277;
R(1,3) = .0146/2*313;
R(1,4) = .0219/2*292;
R(1,5) = .0146/2*620;
R(1,6) = .0146/4*140;
R(6,7) = .0146/2*945;
R(6,8) = .0146/2*423;
R(6,9) = .0822*527;
R(6,10) = .0146/4*785;
R(10,11) = .0219/2*563;
R(1,10) = .0146/4*618;
R(1,12) = .0146*1;
R(6,12) = .0146*1;
R(10,12) = .0146*1;
%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 116S %%%%%%
R(3,13) = .0272*125;
R(13,14) = .0272*5052;
R(14,15) = .0272*3310;
R(15,16) = .0308*90;
R(16,17) = .0308*120;
R(17,18) = .0308*120;
R(18,19) = .0308*370;
R(19,20) = .0308*190;
R(19,21) = .0308*780;
R(21,22) = .1309*135;
R(21,23) = .0308*400;
R(23,24) = .0313*48;
R(24,25) = .0822*14;
R(24,26) = .0822*18;
R(24,27) = .0822*22;
R(24,28) = .0182*1;
```

```
R(28,29) = .0822*15;
R(28,30) = .0822*22;
R(21,31) = .0308*580;
R(31,32) = .1633*80;
R(31,33) = .1633*80;
R(31,34) = .0308*440;
R(34,35) = .0817*180;
R(35,36) = .1633*500;
R(34,37) = .0308*110;
R(37,38) = .0308*260;
R(38,39) = .1633*180;
R(38,40) = .0308*270;
R(40,41) = .0308*160;
R(41,42) = .1633*50;
R(41,43) = .1633*300;
R(16,44) = .0308*292;
R(44,45) = .0308*250;
R(45,46) = .0308*1701;
R(46,47) = .0514*1570;
R(47,48) = .0514*320;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 118 %%%%%%
R(4,49) = .0514*107;
R(49,50) = .0514*4334;
R(50,51) = .0514*963;
R(51,52) = .051*1000;
R(52,53) = .051*1720;
R(53,54) = .051*280;
R(54,55) = .051*560;
R(55,56) = .051*330;
R(56,57) = .0822*60;
R(57,58) = .0822*1020;
R(58,59) = .0822*530;
R(59,60) = .0822*180;
R(60,61) = .0514*1450;
R(61,62) = .0817*70;
R(62,63) = .0817*750;
R(63,64) = .0817*252;
R(64,65) = .0817*260;
R(65,66) = .0817*515;
R(66,67) = .0817*965;
R(67,68) = .0817*125;
R(68,69) = .0817*440;
R(69,70) = .0817*80;
R(69,71) = .0817*60;
R(71,72) = .0817*250;
R(72,73) = .0817*100;
R(73,74) = .0817*150;
R(74,75) = .0817*120;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%% Substation 901 %%%%%
R(5,76) = .0109*258;
R(76,77) = .0109*697;
R(77,78) = .0514*170;
R(78,79) = .0514*303;
R(79,80) = .0822*225;
R(78,81) = .0514*200;
R(77,82) = .0109*171;
R(82,83) = .0109*350;
R(83,84) = .0109*150;
R(82,85) = .0109*4980;
R(85,86) = .0517*150;
R(86,87) = .0517*150;
R(87,88) = .0517*1070;
R(88,89) = .0517*3800;
R(85,90) = .0109*7637;
```

```
R(90,91) = .0109*665;
R(91,92) = .0109*1468;
R(92,93) = .0182*1;
R(93,94) = .0109*3732;
R(94,95) = .0109*11018;
R(95,96) = .0109*383;
R(96,97) = .0109*485;
R(7,97) = .0109*258;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 216 %%%%%
R(8,98) = .0272*129;
R(98,99) = .0272*9144;
R(99,100) = .051*315;
R(100,101) = .051*1955;
R(101,102) = .0308*260;
R(102,103) = .0313/2*135;
R(103,104) = .1037*232;
R(103,105) =  .0313/2*130;
R(103,106) = .1037*86;
R(105,107) = .1037*48;
R(103,108) = .1037*297;
R(105,109) = .1037*490;
R(103,110) = .1037*440;
R(110,111) = .1037*190;
R(110,112) = .1037*80;
R(112,113) = .1037*260;
R(105,114) = .1037*300;
R(114,115) = .1037*175;
R(115,116) = .1037*20;
R(114,117) = .1037*70;
R(105,118) = .0313*313;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 294 %%%%%%
R(11,119) = .0514*111;
R(119,120) = .0514*9054;
R(120,121) = .051*100;
R(121,122) = .051*430;
R(120,123) = .051*300;
R(123,124) = .051*650;
R(124,125) = .051*300;
R(125,126) = .159*175;
R(126,127) = .051*160;
R(127,128) = .051*95;
R(128,129) = .051*95;
R(126,130) = .1309*100;
R(125,131) = .051*330;
R(131,132) = .051*80;
R(131,133) = .051*300;
R(133,134) = .051*130;
R(134,135) = .051*80;
R(135,136) = .0517/2*115;
R(136,137) = .0313*104;
R(136,138) = .1037*92;
R(136,139) = .1309*270;
R(136,140) = .1037*105;
R(136,141) = .1037*97;
R(136,142) = .1037*123;
%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 334 %%%%%%
R(92,143) = .0308*40;
R(143,144) = .0308*4100;
R(144,145) = .0514*125;
R(145,146) = .0514*640;
R(146,147) = .0514*495;
R(147,148) = .0514*120;
R(148,149) = .0514*235;
```

```
R(149,150) = .0517*60;
R(150,151) = .1633*250;
R(150,152) = .1633*220;
R(149,153) = .0514*20;
R(144,154) = .0308*225;
R(154,155) = .0146*344;
R(155,156) = .1309*79;
R(155,157) = .1309*556;
R(157,158) = .1309*29;
R(157,159) = .1309*34;
R(154,160) = .0308*180;
R(160,161) = .0308*362;
R(161,162) = .0308*700;
R(162,163) = .0308*620;
R(163,164) = .0308*300;
R(164,165) = .0308*210;
R(165,166) =.2622*110;
%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 214-224 %%%%%%
R(92,167) = .0313*40;
R(167,168) = .0313*1720;
R(168,169) = .1633*5;
R(92,170) = .0313*40;
R(170,171) = .0313*1700;
R(171,172) = .0313*510;
R(172,173) = .0313*1270;
R(173,174) = .0146*50;
R(174,175) = .0146*247;
R(175,176) = .1037*90;
R(175,177) = .0146*70;
R(177,178) = .0812*5;
R(173,179) = .0146*80;
R(179,180) = .0146*830;
R(180,181) = .0146*690;
R(181,182) = .0219*20;
R(181,183) = .0219*420;
R(180,184) = .1037*80;
R(179,185) = .0146*1200;
R(185,186) = .0146*110;
R(186,187) = .0146*45;
%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 116N %%%%%%
R(45,188) = .0311*112;
R(188,189) = .0311*1058;
R(189,190) = .0311*140;
R(190,191) = .0219*300;
R(191,192) = .0438*90;
R(191,193) = .0822*28;
R(191,194) = .1037*76;
R(194,195) = .1037*144;
R(191,196) = .1037*1;
R(196,197) = .0822*28;
R(197,198) = .0822*22;
R(196,199) = .1309*60;
R(189,200) = .0311*952;
R(200,201) = .0311*285;
R(201,202) = .0308*620;
R(202,203) = .0308*175;
R(203,204) = .0182*1;
R(204,205) = .0146*50;
R(205,206) = .0146*192;
R(206,207) = .0146*30;
R(207,208) = .0146*40;
R(208,209) = .0146*30;
R(208,210) = .1037*135;
R(204,211) = .0146*80;
R(211,212) = .0146*1200;
```

```
R(212,213) = .0146*125;
R(213,214) = .0146*45;
R(211,215) = .0146*830;
R(215,216) = .0219*700;
R(216,217) = .1037*360;
R(216,218) = .0219*435;
R(211,219) = .0146*25;
R(219,220) = .1633*1170;
%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 294 %%%%%%
R(92,221) = .0517*40;
R(221,222) = .0517*2490;
R(222,223) = .0517*290;
R(223,224) = .0514*250;
R(224,225) = .0514*3520;
R(223,226) = .0517*980;
R(226,227) = .0514*580;
R(226,228) = .0517*360;
R(228,229) = .0517*710;
R(229,230) = .0517*540;
R(230,231) = .0517*160;
R(231,232) = .0517*1170;
R(232,233) = .051*70;
R(233,234) = .2622*70;
R(232,235) = .051*1030;
R(235,236) = .051*130;
R(236,237) = .051*530;
R(237,238) = .051*190;
R(238,239) = .051*420;
R(239,240) = .051*1470;
R(240,241) = .051*320;
R(241,242) = .051*150;
R(242,243) = .051*200;
R(243,244) = .051*350;
R(244,245) = .051*1920;
R(245,246) = .254*640;
R(246,247) = .254*320;
R(247,248) = .254*5440;
R(248,249) = .254*240;
R(249,250) = .254*1460;
R(250,251) = .254*1862;
R(251,252) = .254*250;
R(252,253) = .254*740;
R(253,254) = .254*280;
R(245,255) = .051*1420;
R(255,256) = .0822*1320;
R(256,257) = .0822*1460;
R(257,258) = .0822*300;
R(258,259) = .0822*720;
R(242,260) = .051*640;
R(260,261) = .051*640;
R(261,262) = .051*80;
R(262,263) = .1633*140;
R(262,264) = .051*100;
R(264,265) = .051*105;
R(262,266) = .051*360;
R(266,267) = .051*460;
R(261,268) = .0514*60;
R(268,269) = .0514*220;
R(269,270) = .0514*120;
R(270,271) = .0514*680;
R(271,272) = .0514*195;
R(272,273) = .0514*180;
R(273,274) = .0514*240;
R(274,275) = .0514*60;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

Pbase = 4000000;
vbase = 30000;
Rbase = vbase^2/Pbase;

R = 2*R/1000/Rbase;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%% Main Substation %%%%%
Pload(1) = 24.3;    %Bus 2
P_locations(1) = 2;
Pload(2) = 24.3;    %Bus 9
P_locations(2) = 9;
%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%% Feeder 116S %%%%%%
Pload(3) = 16.9;    %Bus 20
P_locations(3) = 20;
Pload(4) = 1.7;    %Bus 22
P_locations(4) = 22;
Pload(5) = 1.8;    %Bus 25
P_locations(5) = 25;
Pload(6) = 159.6;    %Bus 26
P_locations(6) = 26;
Pload(7) = 13.1;    %Bus 27
P_locations(7) = 27;
Pload(8) = 23.6;    %Bus 29
P_locations(8) = 29;
Pload(9) = 33.6;    %Bus 30
P_locations(9) = 30;
Pload(10) = 1.8;    %Bus 32
P_locations(10) = 32;
Pload(11) = 6;    %Bus 33
P_locations(11) = 33;
Pload(12) = 48.8;    %Bus 36
P_locations(12) = 36;
Pload(13) = 81.8;    %Bus 39
P_locations(13) = 39;
Pload(14) = 145.3;    %Bus 42
P_locations(14) = 42;
Pload(15) = 15.0;    %Bus 43
P_locations(15) = 43;
Pload(16) = 1.8;    %Bus 48
P_locations(16) = 48;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%% Feeder 118 %%%%%%%%%%%%
Pload(17) = .2;    %Bus 52
P_locations(17) = 52;
Pload(18) = 35;    %Bus 53
P_locations(18) = 53;
Pload(19) = 64.2;    %Bus 54
P_locations(19) = 54;
Pload(20) = 17.5;    %Bus 58
P_locations(20) = 58;
Pload(21) = 34.9;    %Bus 70
```

```
P_locations(21) = 70;
Pload(22) = 570.4;    %Bus 73
P_locations(22) = 73;
Pload(23) = 279.4;    %Bus 75
P_locations(23) = 75;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Substation 901 %%%%%%%%
Pload(24) = 78.2;    %Bus 80
P_locations(24) = 80;
Pload(25) = 6.5;    %Bus 81
P_locations(25) = 81;
Pload(26) = 335.1;    %Bus 84
P_locations(26) = 84;
Pload(27) = 6.7;    %Bus 89
P_locations(27) = 89;
Pload(28) = 6;    %Bus 92
P_locations(28) = 92;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 216 %%%%%%%%
Pload(29) = 165;    %Bus 104
P_locations(29) = 104;
Pload(30) = 212.8;    %Bus 106
P_locations(30) = 106;
Pload(31) = 262.1;    %Bus 107
P_locations(31) = 107;
Pload(32) = 558.8;    %Bus 108
P_locations(32) = 108;
Pload(33) = 3.9;    %Bus 109
P_locations(33) = 109;
Pload(34) = 266.6;    %Bus 111
P_locations(34) = 111;
Pload(35) = 368.2;    %Bus 113
P_locations(35) = 113;
Pload(36) = 266.6;    %Bus 116
P_locations(36) = 116;
Pload(37) = 368.2;    %Bus 117
P_locations(37) = 117;
Pload(38) = 190.5;    %Bus 118
P_locations(38) = 118;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 294 %%%%%%%%
Pload(39) = 175.1;    %Bus 122
P_locations(39) = 122;
Pload(40) = 13.4;    %Bus 128
P_locations(40) = 128;
Pload(41) = 445.8;    %Bus 130
P_locations(41) = 130;
Pload(42) = 13.7;    %Bus 132
P_locations(42) = 132;
Pload(43) = 251.4;    %Bus 137
P_locations(43) = 137;
Pload(44) = 290.9;    %Bus 138
P_locations(44) = 138;
Pload(45) = 290.9;    %Bus 139
P_locations(45) = 139;
Pload(46) = 290.9;    %Bus 140
P_locations(46) = 140;
Pload(47) = 290.9;    %Bus 141
P_locations(47) = 141;
Pload(48) = 290.9;    %Bus 142
P_locations(48) = 142;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 334 %%%%%%%%
Pload(49) = 95.3;    %Bus 147
```

```
P_locations(49) = 147;
Pload(50) = 17.0;    %Bus 148
P_locations(50) = 148;
Pload(51) = 53.4;    %Bus 151
P_locations(51) = 151;
Pload(52) = 54.74;    %Bus 152
P_locations(52) = 152;
Pload(53) = 34.5;    %Bus 153
P_locations(53) = 153;
Pload(54) = 190.7;    %Bus 156
P_locations(54) = 156;
Pload(55) = 258.5;    %Bus 158
P_locations(55) = 158;
Pload(56) = 258.5;    %Bus 159
P_locations(56) = 159;
Pload(57) = 125.7;    %Bus 166
P_locations(57) = 166;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 214-224 %%%%%%%%
Pload(58) = 638.4;    %Bus 176
P_locations(58) = 176;
Pload(59) = 638.4;    %Bus 178
P_locations(59) = 178;
Pload(60) = 256.5;    %Bus 182
P_locations(60) = 182;
Pload(61) = 101.6;    %Bus 183
P_locations(61) = 183;
Pload(62) = 97.0;    %Bus 184
P_locations(62) = 184;
Pload(63) = 837.5;    %Bus 185
P_locations(63) = 185;
Pload(64) = 409.1;    %Bus 186
P_locations(64) = 186;
Pload(65) = 601.5;    %Bus 187
P_locations(65) = 187;
Pload(66) = 6;    %Bus 169
P_locations(66) = 169;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 116N %%%%%%%%
Pload(67) = 3729.1;    %Bus 192
P_locations(67) = 192;
Pload(68) = 148.3;    %Bus 193
P_locations(68) = 193;
Pload(69) = 222.4;    %Bus 194
P_locations(69) = 194;
Pload(70) = 105.9;    %Bus 195
P_locations(70) = 195;
Pload(71) = 148.3;    %Bus 197
P_locations(71) = 197;
Pload(72) = 148.3;    %Bus 198
P_locations(72) = 198;
Pload(73) = 285.9;    %Bus 199
P_locations(73) = 199;
Pload(74) = 1.8;      %Bus 203
P_locations(74) = 203;
Pload(75) = 638.4;        %Bus 207
P_locations(75) = 207;
Pload(76) = 638.4;        %Bus 210
P_locations(76) = 210;
Pload(77) = 871.2;        %Bus 212
P_locations(77) = 212;
Pload(78) = 464.4;        %Bus 213
P_locations(78) = 213;
Pload(79) = 180.2;        %Bus 214
P_locations(79) = 214;
Pload(80) = 33.1;        %Bus 217
P_locations(80) = 217;
```

```
Pload(81) = 101.6;        %Bus 218
P_locations(81) = 218;
Pload(82) = 1.3;        %Bus 220
P_locations(82) = 220;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 234 %%%%%%%%%%%
Pload(83) = 6.9;        %Bus 225
P_locations(83) = 225;
Pload(84) = 1.4;        %Bus 227
P_locations(84) = 227;
Pload(85) = 69.4;        %Bus 234
P_locations(85) = 234;
Pload(86) = 102.5;        %Bus 248
P_locations(86) = 248;
Pload(87) = 3.2;        %Bus 249
P_locations(87) = 249;
Pload(88) = 7.3;        %Bus 253
P_locations(83) = 253;
Pload(83) = 44.9;        %Bus 254
P_locations(88) = 254;
Pload(89) = 4.1;        %Bus 255
P_locations(89) = 255;
Pload(90) = 38.7;        %Bus 259
P_locations(90) = 259;
Pload(91) = 3.7;        %Bus 263
P_locations(91) = 263;
Pload(92) = 14.0;        %Bus 264
P_locations(92) = 264;
Pload(93) = 1.7;        %Bus 265
P_locations(93) = 265;
Pload(94) = 112.0;        %Bus 267
P_locations(94) = 267;
Pload(95) = 60.9;        %Bus 269
P_locations(95) = 269;
Pload(96) = 68.8;        %Bus 270
P_locations(96) = 270;
Pload(97) = 6.6;        %Bus 271
P_locations(97) = 271;
Pload(98) = 5.0;        %Bus 272
P_locations(98) = 272;
Pload(99) = 35.1;        %Bus 273
P_locations(99) = 273;
Pload(100) = 16.9;        %Bus 275
P_locations(100) = 275;

exclude = [137, 192];
loads = length(Pload);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% CALCULATE ADMITTANCE MATRIX %%%%%%%%%%%%%%
for i =1:buses
     for k = 1:buses
          if i ~= k
               if (R(i,k)) == 0
                   Y(i,k) = 0;
               else
                   Y(i,k) = -1/(R(i,k));
               end;
          else
               Y(i,i) = 0;
          end;
     end;
end;

for i = 1:buses
```

```
     Y(i,i) = -sum(Y(:,i));
end;

%%%%%%%%%%%% FINDING OPTIMUM  %%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

stop = 100;         %Number of fells/iterations
store = zeros(stop,stop);    %information storage
iteration = 0;
for z = 1:stop     %Begin loop

%%%%%%%%%% Genetic Algorithm Parameters %%%%%%%%%%%
iteration = iteration + 1
k = iteration; %number of fuel cells in system
n = 10 + 10*round(iteration);
r = 500*round(iteration/5);% amount of random variations tried at once
iterations = 1;



file='DC_load_flow_vs1';

for w=1:k
    pool(w,:)=[1 (buses+loads)];
end

%   Let's create a random initial popluation of size 20.

for i = 1:1
    initPop = initializega(r,pool,file);
    [x endPop] = ga(pool,file,[],initPop,[1e-6 1 1],'maxGenTerm',n);
end


%%%%%%%%%%%% USING GA RESULTS TO GET ENTIRE SYSTEM PARAMETERS %%%%%%%%%
for i = 1:length(x)
    store(z,i) = x(i);
end;
```

8 APPENDIX F (CODE FOR EVALUATION OF DC LOSSES)

```
clear all;
clc;

tic

%%%%%%%%%%%%% LV SYSTEM PROFILES  %%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

eff = 0.90;
conv_eff = .90;
inv_eff = .97
gen_max = 0;
Pbase = 4000000;
vbase = 30000;
vbase2 = 5000;
Rbase = vbase^2/Pbase;
Rbase2 = vbase2^2/Pbase;

%%%%%%%%%%% 216 LV Systems 1 %%%%%%%%%%%%

swing_bus = 1;
buses = 4;

R = zeros(buses,buses);

R(1,2) = .00365*27;
R(2,3) = .0219*144;
R(3,4) = .0219*20;

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

Pload(1) = 505.6/inv_eff;
P_locations(1) = 3;
Pload(2) = 505.6/inv_eff;
P_locations(2) = 4;


exclude = [3,4];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load1 = gen*Pbase/conv_eff;
losses1 = losses*Pbase+(load1-gen*Pbase)+(1/inv_eff-1)*(Pload(1)*inv_eff +
Pload(2)*inv_eff)*1000;

%pause;
```

```
clc

clear Pload;
clear P_locations
clear R;

%%%%%%%%%%% 216 LV Systems 2 %%%%%%%%%%%

swing_bus = 1;
buses = 3;

R = zeros(buses,buses);

R(1,2) = .00365*43;
R(2,3) = .0517*109;


%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

Pload(1) = 131;
P_locations(1) = 3;


exclude = [];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load2 = gen*Pbase/conv_eff;
losses2 = losses*Pbase+(load2-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%% 2632 %%%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 47;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .0146*160;
R(2,3) = .0514*150;
R(3,4) = .0514*350;
R(4,5) = .0514*80;
R(4,6) = .0514*140;
```

```
R(6,7) = .0514*240;
R(3,8) = .0514*170;
R(8,9) = .0514*100;
R(9,10) = .0514*100;
R(10,11) = .0517*100;
R(11,12) = .0517*80;
R(12,13) = .0517*120;
R(13,14) = .0517*30;
R(14,15) = .0517*110;
R(15,16) = .1633*40;

R(1,17) = .0146*95;
R(17,18) = .0346*140;
R(18,19) = .0219*59;
R(17,20) = .0346*240;
R(20,21) = .0219*55;

R(1,22) = .0146*83;
R(22,23) = .0514*890;
R(23,24) = .0514*160;
R(23,25) = .0514*170;
R(25,26) = .0817*80;
R(26,27) = .0817*60;
R(26,28) = .0817*200;

R(1,29) = .0146*165;
R(29,30) = .0514*260;
R(30,31) = .0514*110;
R(31,32) = .0514*40;
R(31,33) = .0514*20;

R(1,34) = .0146*140;
R(34,35) = .0346*220;
R(35,36) = .26*100;
R(36,37) = .4169*133;
R(35,38) = .26*120;
R(38,39) = .26*530;
R(35,40) = .0346*430;
R(40,41) = .0346*180;
R(41,42) = .0219*145;
R(42,43) = .1037*101;
R(43,44) = .2622*20;
R(41,45) = .1633*160;
R(45,46) = .1633*180;
R(45,47) = .1633*50;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%


%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Pload(1) = 39.9;    %Bus 5
P_locations(1) = 5;
Pload(2) = 28.1;    %Bus 6
```

```
P_locations(2) = 6;
Pload(3) = 25.9;    %Bus 7
P_locations(3) = 7;
Pload(4) = 57.8;    %Bus 13
P_locations(4) = 13;
Pload(5) = 1.16;    %Bus 14
P_locations(5) = 14;
Pload(6) = 3.7;    %Bus 16
P_locations(6) = 16;
Pload(7) = 124.9;    %Bus 19
P_locations(7) = 19;
Pload(8) = 4.0;    %Bus 20
P_locations(8) = 20;
Pload(9) = 184.9;    %Bus 21
P_locations(9) = 21;
Pload(10) = 20.6;    %Bus 24
P_locations(10) = 24;
Pload(11) = 20.8;    %Bus 27
P_locations(11) = 27;
Pload(12) = 4.9;    %Bus 28
P_locations(12) = 28;
Pload(13) = 34.0;    %Bus 31
P_locations(13) = 31;
Pload(14) = 4.0;    %Bus 32
P_locations(14) = 32;
Pload(15) = 58.0;    %Bus 33
P_locations(15) = 33;
Pload(16) = 27.2;    %Bus 37
P_locations(16) = 37;
Pload(17) = 5.5;    %Bus 38
P_locations(17) = 38;
Pload(18) = 105.1;    %Bus 42
P_locations(18) = 42;
Pload(19) = 150.4/inv_eff;    %Bus 44
P_locations(19) = 44;
Pload(20) = 14.0;    %Bus 45
P_locations(20) = 45;
Pload(21) = .9;    %Bus 47
P_locations(21) = 47;

exclude = [44];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load3 = gen*Pbase/conv_eff;
losses3 = losses*Pbase+(load3-gen*Pbase)+(1/inv_eff-1)*(Pload(19)*inv_eff)*1000;

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%



%%%%%%%%%%%%%%%%%% 4000 N %%%%%%%%%%%%%%%%%%%
swing_bus = 31;
buses = 31;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
R = zeros(buses,buses);

R(1,2) = .0517*200;
R(2,3) = .0517*153;
R(3,4) = .0517*170;
R(4,5) = .0517*330;
R(5,6) = .0517*50;
R(1,7) = .0517*270;
R(7,8) = .0517*80;
R(8,9) = .0517*90;
R(9,10) = .0517*170;
R(10,11) = .0517*165;
R(11,12) = .0517*220;
R(12,13) = .0817*170;
R(12,14) = .0517*340;
R(14,15) = .0517*520;
R(15,16) = .0517*70;
R(12,17) = .0517*255;
R(17,18) = .0517*135;
R(18,19) = .0517*260;
R(19,20) = .0517*530;
R(1,21) = .2622*320;
R(21,22) = .2622*390;
R(22,23) = .2622*160;
R(23,24) = .26*150;
R(23,25) = .0517*320;
R(25,26) = .0517*50;
R(25,27) = .26*150;
R(23,28) = .2622*1090;
R(28,29) = .2622*300;
R(1,30) = .0514*125;
R(30,31) = .0514*155;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

Pload(1) = .18;    %Bus 4
P_locations(1) = 4;
Pload(2) = 60.9;    %Bus 5
P_locations(2) = 5;
Pload(3) = 3.7;    %Bus 6
P_locations(3) = 6;
Pload(4) = 19.7;    %Bus 7
P_locations(4) = 7;
Pload(5) = 42.8;    %Bus 9
P_locations(5) = 9;
Pload(6) = 16.2;    %Bus 10
P_locations(6) = 10;
Pload(7) = 93.3;    %Bus 13
P_locations(7) = 13;
Pload(8) = 8.5;    %Bus 14
P_locations(8) = 14;
Pload(9) = 10.1;    %Bus 15
P_locations(9) = 15;
```

```
Pload(10) = 12.6;    %Bus 16
P_locations(10) = 16;
Pload(11) = 11.9;    %Bus 17
P_locations(11) = 17;
Pload(12) = 3.9;    %Bus 18
P_locations(12) = 18;
Pload(13) = .47;    %Bus 19
P_locations(13) = 19;
Pload(14) = 6.6;    %Bus 20
P_locations(14) = 20;
Pload(15) = 14.9;    %Bus 23
P_locations(15) = 23;
Pload(16) = 20.3;    %Bus 24
P_locations(16) = 24;
Pload(17) = 37.2;    %Bus 25
P_locations(17) = 25;
Pload(18) = 22.8;    %Bus 26
P_locations(18) = 26;
Pload(19) = 5.9;    %Bus 27
P_locations(19) = 27;
Pload(20) = 1.5;    %Bus 29
P_locations(20) = 29;

exclude = [];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load4 = gen*Pbase/conv_eff;
losses4 = losses*Pbase+(load4-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%% 4000 E %%%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 28;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .0146*1043;
R(2,3) = .0438*317;
R(1,4) = .0313*44;
R(4,5) = .0313*480;
R(5,6) = .0313*325;
R(5,7) = .0313*280;
R(7,8) = .0219*200;
R(7,9) = .0313*185;
R(9,10) = .0219*85;
R(9,11) = .0313*275;
R(11,12) = .0313*33;
R(12,13) = .0313*225;
R(1,14) = .0514*155;
R(14,15) = .0517*70;
R(15,16) = .0517*243;
R(16,17) = .0517*248;
```

```
R(17,18) = .0438*135;
R(18,19) = .0438*25;
R(14,20) = .0517*740;
R(20,21) = .0517*200;
R(21,22) = .0517*90;
R(22,23) = .0517*320;
R(23,24) = .0346*111;
R(24,25) = .0517*20;
R(25,26) = .1633*190;
R(1,27) = .0219*45;
R(27,28) = .0517*20;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

Pload(1) = 346.2;    %Bus 3
P_locations(1) = 3;
Pload(2) = 12.53;    %Bus 6
P_locations(2) = 6;
Pload(3) = 154.9;    %Bus 8
P_locations(3) = 8;
Pload(4) = 35.9;    %Bus 10
P_locations(4) = 10;
Pload(5) = 53.7;    %Bus 11
P_locations(5) = 11;
Pload(6) = 22.4;    %Bus 12
P_locations(6) = 12;
Pload(7) = 77.7;    %Bus 13
P_locations(7) = 13;
Pload(8) = 22.5;    %Bus 16
P_locations(8) = 16;

Pload(9) = 176.4;    %Bus 18
P_locations(9) = 18;
Pload(10) = 22.6;    %Bus 19
P_locations(10) = 19;
Pload(11) = 166.8;    %Bus 21
P_locations(11) = 21;
Pload(12) = 76.6;    %Bus 24
P_locations(12) = 24;
Pload(13) = 13.3;    %Bus 26
P_locations(13) = 26;
Pload(14) = 5.1;    %Bus 28
P_locations(14) = 28;

exclude = [];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load5 = gen*Pbase/conv_eff;
```

```
losses5 = losses*Pbase+(load5-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%% 4000 W %%%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 12;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .01565*1043;
R(2,3) = .0219*60;
R(2,4) = .0438*25;
R(2,5) = .4169*100;
R(2,6) = .6629*270;
R(2,7) = .1633*280;
R(1,8) = .0219*1080;
R(8,9) = .0219*120;
R(8,10) = .0219*450;
R(10,11) = .0517*20;
R(10,12) = .0517*30;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

Pload(1) = 6.25;    %Bus 3
P_locations(1) = 3;
Pload(2) = 428.5;    %Bus 4
P_locations(2) = 4;
Pload(3) = 10.5;    %Bus 5
P_locations(3) = 5;
Pload(4) = 10.5;    %Bus 6
P_locations(4) = 6;
Pload(5) = 10.5;    %Bus 7
P_locations(5) = 7;
Pload(6) = 11.2;    %Bus 9
P_locations(6) = 9;
Pload(7) = 49.6;    %Bus 11
P_locations(7) = 11;
Pload(8) = 49.6;    %Bus 12
P_locations(8) = 12;

exclude = [];
```

```
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load6 = gen*Pbase/conv_eff;
losses6 = losses*Pbase+(load6-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%% 3000 E %%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 35;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .0146*136;
R(2,3) = .0514*50;
R(3,4) = .1633*65;
R(3,5) = .0514*110;
R(5,6) = .0514*280;
R(6,7) = .0514*40;
R(7,8) = .0517*40;
R(6,9) = .0514*60;
R(9,10) = .0514*70;
R(10,11) = .0514*10;

R(1,12) = .0146*170;
R(12,13) = .0517*230;
R(13,14) = .0817*140;
R(13,15) = .0517*110;
R(15,16) = .0817*170;
R(15,17) = .0517*220;

R(1,18) = .0146*150;
R(18,19) = .0514*160;
R(19,20) = .0514*255;
R(20,21) = .0517*65;
R(21,22) = .0517*55;
R(21,23) = .0517*100;
R(23,24) = .0517*65;

R(1,25) = .0146*138;
R(25,26) = .0514*620;
R(26,27) = .0514*160;
R(27,28) = .0514*220;
R(28,29) = .0514*100;
R(29,30) = .0514*130;
R(30,31) = .0822*200;
R(31,32) = .0822*180;
R(32,33) = .0517*50;
R(33,34) = .0517*185;
R(34,35) = .2622*105;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Pload(1) = 31.9;    %Bus 4
P_locations(1) = 4;
Pload(2) = 12.8;    %Bus 7
P_locations(2) = 7;
Pload(3) = 21.3;    %Bus 10
P_locations(3) = 10;
Pload(4) = 56.9;    %Bus 11
P_locations(4) = 11;
Pload(5) = 31.9;    %Bus 14
P_locations(5) = 14;
Pload(6) = 104.10;    %Bus 16
P_locations(6) = 16;
Pload(7) = 60.9;    %Bus 17
P_locations(7) = 17;
Pload(8) = 3.4;    %Bus 19
P_locations(8) = 19;
Pload(9) = 33.83;    %Bus 22
P_locations(9) = 22;
Pload(10) = 157.2;    %Bus 24
P_locations(10) = 24;
Pload(11) = 27.01;    %Bus 27
P_locations(11) = 27;
Pload(12) = 217.7;    %Bus 29
P_locations(12) = 29;
Pload(13) = 39.3;    %Bus 31
P_locations(13) = 31;
Pload(14) = 165.0;    %Bus 32
P_locations(14) = 32;
Pload(15) = 39.6;    %Bus 33
P_locations(15) = 33;
Pload(16) = 46.7;    %Bus 35
P_locations(16) = 35;


exclude = [];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load7 = gen*Pbase/conv_eff;
losses7 = losses*Pbase+(load7-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
%%%%%%%%%%%%%%%%%% 3000 W %%%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 66;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .0146*225;
R(2,3) = .0514*350;
R(3,4) = .0514*360;
R(4,5) = .0517*80;
R(5,6) = .0517*100;
R(6,7) = .2622*30;
R(6,8) = .0517*60;
R(6,9) = .0517*110;

R(4,10) = .0517*190;
R(10,11) = .0517*70;
R(11,12) = .414*40;
R(11,13) = .1633*100;
R(13,14) = .0517*65;

R(1,15) = .0146*118;
R(15,16) = .0346*3210;
R(16,17) = .0517*44;
R(17,18) = .0517*15;
R(18,19) = .0517*95;
R(16,20) = .0346*70;
R(20,21) = .0346*8;
R(21,22) = .1633*30;


R(1,23) = .0146*120;
R(23,24) = .0517*135;
R(24,25) = .0517*275;
R(25,26) = .0517*70;
R(26,27) = .0517*220;

R(27,28) = .0517*490;
R(28,29) = .0517*570;
R(29,30) = .0517*390;
R(30,31) = .0517*360;
R(31,32) = .2622*85;
R(31,33) = .0517*65;
R(33,34) = .0517*120;
R(34,35) = .0517*170;
R(35,36) = .1633*60;
R(35,37) = .0817*360;
R(37,38) = .0817*100;
R(38,39) = .0817*45;
R(38,40) = .0817*400;
R(34,41) = .0517*160;
R(41,42) = .260*50;
R(41,43) = .0514*50;
R(43,44) = .0514*60;

R(43,45) = .0795*180;
R(45,46) = .0795*70;
R(45,47) = .0795*50;
R(45,48) = .0795*370;
R(48,49) = .26*45;

R(1,50) = .0146*217;
R(50,51) = .0514*80;
```

```
R(51,52) = .0514*400;
R(52,53) = .0514*140;
R(53,54) = .0514*130;
R(54,55) = .0438*113;
R(54,56) = .0514*230;
R(56,57) = .0514*89;
R(57,58) = .0514*120;
R(58,59) = .1633*150;

R(58,60) = .0514*170;
R(60,61) = .0517*170;
R(61,62) = .0517*120;
R(62,63) = .0517*100;
R(63,64) = .0517*100;
R(64,65) = .0517*200;
R(65,66) = .0517*200;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Pload(1) = 8.4;    %Bus 5
P_locations(1) = 5;
Pload(2) = 48.5;    %Bus 7
P_locations(2) = 7;
Pload(3) = 67.9;    %Bus 8
P_locations(3) = 8;
Pload(4) = 91.2;    %Bus 9
P_locations(4) = 9;
Pload(5) = 53.2;    %Bus 12
P_locations(5) = 12;
Pload(6) = 33.6;    %Bus 14
P_locations(6) = 14;
Pload(7) = 522.1/inv_eff;    %Bus 19
P_locations(7) = 19;
Pload(8) = 2.97;    %Bus 22
P_locations(8) = 22;
Pload(9) = 10.0;    %Bus 30
P_locations(9) = 30;
Pload(10) = 35.3;    %Bus 32
P_locations(10) = 32;
Pload(11) = 19.1;    %Bus 36
P_locations(11) = 36;
Pload(12) = 68.7;    %Bus 39
P_locations(12) = 39;
Pload(13) = 18.4;    %Bus 40
P_locations(13) = 40;
Pload(14) = 41.7;    %Bus 42
P_locations(14) = 42;
Pload(15) = 7.8;    %Bus 44
P_locations(15) = 44;
Pload(16) = 24.8;    %Bus 46
P_locations(16) = 46;
Pload(17) = 12.8;    %Bus 40
```

```
P_locations(17) = 47;
Pload(18) = 54.2;    %Bus 42
P_locations(18) = 49;
Pload(19) = 197.6;    %Bus 44
P_locations(19) = 55;
Pload(20) = 72.9;    %Bus 46
P_locations(20) = 59;
Pload(21) = 15.2;    %Bus 40
P_locations(21) = 61;
Pload(22) = 10.0;    %Bus 42
P_locations(22) = 63;
Pload(23) = 3.5;    %Bus 44
P_locations(23) = 64;
Pload(24) = 14.1;    %Bus 46
P_locations(24) = 65;
Pload(25) = 63.3;    %Bus 46
P_locations(25) = 66;


exclude = [7];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load8 = gen*Pbase/conv_eff
losses8 = losses*Pbase+(load8-gen*Pbase)+(1/inv_eff-1)*(Pload(7)*1000*inv_eff)

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%%%%%%%%%%%%%%%%% Melton %%%%%%%%%%%%%%%%%%%
swing_bus = 1;
buses = 9;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

R(1,2) = .2622*120;
R(2,3) = .2622*680;
R(3,4) = .2622*270;
R(3,5) = .2622*660;
R(5,6) = .2622*150;
R(5,7) = .2622*260;
R(7,8) = .2622*80;
R(5,9) = .2622*660;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;
```

```
%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase2;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
Pload(1) = 34.9;     %Bus 5
P_locations(1) = 3;
Pload(2) = 23.3;     %Bus 7
P_locations(2) = 4;
Pload(3) = 69.9;     %Bus 8
P_locations(3) = 6;
Pload(4) = 46.6;     %Bus 9
P_locations(4) = 7;


exclude = [];
loads = length(Pload);

%%%%%%% Determining net generation and losses
[losses, gen] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);

%%%%%%% Converting from pu form
load9 = gen*Pbase/conv_eff;
losses9 = losses*Pbase+(load9-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%% SWSA %%%%%%%%%%%%
gen = 109.6/Pbase/eff
load10 = gen*Pbase/conv_eff;
losses10 = losses*Pbase+(load10-gen*Pbase);

%pause;
clc

clear Pload;
clear P_locations
clear R;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%% HV SYSTEM PROFILES  %%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%% System Parameters %%%%%%%%%%%

swing_bus = 12;
buses = 284;

%%%%%%% CREATING RESISTANCE MATRIX %%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

R = zeros(buses,buses);

%%%% Main Substation %%%%
R(1,2) = .0822*277;
R(1,3) = .0146/2*313;
R(1,4) = .0219/2*292;
```

```
R(1,5) = .0146/2*620;
R(1,6) = .0146/4*140;
R(6,7) = .0146/2*945;
R(6,8) = .0146/2*423;
R(6,9) = .0822*527;
R(6,10) = .0146/4*785;
R(10,11) = .0219/2*563;
R(1,10) = .0146/4*618;
R(1,12) = .0146*1;
R(6,12) = .0146*1;
R(10,12) = .0146*1;
%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 116S %%%%%%
R(3,13) = .0272*125;
R(13,14) = .0272*5052;
R(14,15) = .0272*3310;
R(15,16) = .0308*90;
R(16,17) = .0308*120;
R(17,18) = .0308*120;
R(18,19) = .0308*370;
R(19,20) = .0308*190;
R(19,21) = .0308*780;
R(21,22) = .1309*135;
R(21,23) = .0308*400;
R(23,24) = .0313*48;
R(24,25) = .0822*14;
R(24,26) = .0822*18;
R(24,27) = .0822*22;
R(24,28) = .0182*1;
R(28,29) = .0822*15;
R(28,30) = .0822*22;
R(21,31) = .0308*580;
R(31,32) = .1633*80;
R(31,33) = .1633*80;
R(31,34) = .0308*440;
R(34,35) = .0817*180;
R(35,36) = .1633*500;
R(34,37) = .0308*110;
R(37,38) = .0308*260;
R(38,39) = .1633*180;
R(38,40) = .0308*270;
R(40,41) = .0308*160;
R(41,42) = .1633*50;
R(41,43) = .1633*300;
R(16,44) = .0308*292;
R(44,45) = .0308*250;
R(45,46) = .0308*1701;
R(46,47) = .0514*1570;
R(47,48) = .0514*320;
R(15,282) = .0308*115;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 118 %%%%%%
R(4,49) = .0514*107;
R(49,50) = .0514*4334;
R(50,51) = .0514*963;
R(51,52) = .051*1000;
R(52,53) = .051*1720;
R(53,54) = .051*280;
R(54,55) = .051*560;
R(55,56) = .051*330;
R(56,57) = .0822*60;
R(57,58) = .0822*1020;
R(58,59) = .0822*530;
R(59,60) = .0822*180;
R(60,61) = .0514*1450;
R(61,62) = .0817*70;
R(62,63) = .0817*750;
```

```
R(63,64) = .0817*252;
R(64,65) = .0817*260;
R(65,66) = .0817*515;
R(66,67) = .0817*965;
R(67,68) = .0817*125;
R(68,69) = .0817*440;
R(69,70) = .0817*80;
R(69,71) = .0817*60;
R(71,72) = .0817*250;
R(72,73) = .0817*100;
R(73,74) = .0817*150;
R(74,75) = .0817*120;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%


%%% Substation 901 %%%%%
R(5,76) = .0109*258;
R(76,77) = .0109*697;
R(77,78) = .0514*170;
R(78,79) = .0514*303;
R(79,80) = .0822*225;
R(78,81) = .0514*200;
R(77,82) = .0109*171;
R(82,83) = .0109*350;
R(83,84) = .0109*150;
R(82,85) = .0109*4980;
R(85,86) = .0517*150;
R(86,87) = .0517*150;
R(87,88) = .0517*1070;
R(88,89) = .0517*3800;
R(85,90) = .0109*7637;
R(90,91) = .0109*665;
R(91,92) = .0109*1468;
R(92,93) = .0182*1;
R(93,94) = .0109*3732;
R(94,95) = .0109*11018;
R(95,96) = .0109*383;
R(96,97) = .0109*485;
R(7,97) = .0109*258;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 216 %%%%%
R(8,98) = .0272*129;
R(98,99) = .0272*9144;
R(99,100) = .051*315;
R(100,101) = .051*1955;
R(101,102) = .0308*260;
R(102,103) = .0313/2*135;
R(103,104) = .1037*232;
R(103,105) =  .0313/2*130;
R(103,106) = .1037*86;
R(105,107) = .1037*48;
R(103,108) = .1037*297;
R(105,109) = .1037*490;
R(103,110) = .1037*440;
R(110,111) = .1037*190;
R(110,112) = .1037*80;
R(112,113) = .1037*260;
R(105,114) = .1037*300;
R(114,115) = .1037*175;
R(115,116) = .1037*20;
R(114,117) = .1037*70;
R(105,118) = .0313*313;
R(103,276) = .0313*38;
R(276,277) = .0313*21;
R(105,278) = .0313*73;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 294 %%%%%%
```

```
R(11,119) = .0514*111;
R(119,120) = .0514*9054;
R(120,121) = .051*100;
R(121,122) = .051*430;
R(120,123) = .051*300;
R(123,124) = .051*650;
R(124,125) = .051*300;
R(125,126) = .159*175;
R(126,127) = .051*160;
R(127,128) = .051*95;
R(128,129) = .051*95;
R(126,130) = .1309*100;
R(125,131) = .051*330;
R(131,132) = .051*80;
R(131,133) = .051*300;
R(133,134) = .051*130;
R(134,135) = .051*80;
R(135,136) = .0517/2*115;
R(136,137) = .0313*104;
R(136,138) = .1037*92;
R(136,139) = .1309*270;
R(136,140) = .1037*105;
R(136,141) = .1037*97;
R(136,142) = .1037*123;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%% Feeder 344 %%%%%%
R(92,143) = .0308*40;
R(143,144) = .0308*4100;
R(144,145) = .0514*125;
R(145,146) = .0514*640;
R(146,147) = .0514*495;
R(147,148) = .0514*120;
R(148,149) = .0514*235;
R(149,150) = .0517*60;
R(150,151) = .1633*250;
R(150,152) = .1633*220;
R(149,153) = .0514*20;
R(144,154) = .0308*225;
R(154,155) = .0146*344;
R(155,156) = .1309*79;
R(155,157) = .1309*556;
R(157,158) = .1309*29;
R(157,159) = .1309*34;
R(154,160) = .0308*180;
R(160,161) = .0308*362;
R(161,162) = .0308*700;
R(162,163) = .0308*620;
R(163,164) = .0308*300;
R(164,165) = .0308*210;
R(165,166) = .2622*110;
R(164,279) = .0795*510;
R(279,280) = .0313*155;
R(280,281) = .0313*23;
%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 214-224 %%%%%%
R(92,167) = .0313*40;
R(167,168) = .0313*1720;
R(168,169) = .1633*5;
R(92,170) = .0313*40;
R(170,171) = .0313*1700;
R(171,172) = .0313*510;
R(172,173) = .0313*1270;
R(173,174) = .0146*50;
R(174,175) = .0146*247;
R(175,176) = .1037*90;
R(175,177) = .0146*70;
R(177,178) = .0812*5;
```

```
R(173,179) = .0146*80;
R(179,180) = .0146*830;
R(180,181) = .0146*690;
R(181,182) = .0219*20;
R(181,183) = .0219*420;
R(180,184) = .1037*80;
R(179,185) = .0146*1200;
R(185,186) = .0146*110;
R(186,187) = .0146*45;
R(168,283) = .0001;
R(168,284) = .0001;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 116N %%%%%%
R(45,188) = .0311*112;
R(188,189) = .0311*1058;
R(189,190) = .0311*140;
R(190,191) = .0219*300;
R(191,192) = .0438*90;
R(191,193) = .0822*28;
R(191,194) = .1037*76;
R(194,195) = .1037*144;
R(191,196) = .1037*1;
R(196,197) = .0822*28;
R(197,198) = .0822*22;
R(196,199) = .1309*60;
R(189,200) = .0311*952;
R(200,201) = .0311*285;
R(201,202) = .0308*620;
R(202,203) = .0308*175;
R(203,204) = .0182*1;
R(204,205) = .0146*50;
R(205,206) = .0146*192;
R(206,207) = .0146*30;
R(207,208) = .0146*40;
R(208,209) = .0146*30;
R(208,210) = .1037*135;
R(204,211) = .0146*80;
R(211,212) = .0146*1200;
R(212,213) = .0146*125;
R(213,214) = .0146*45;
R(211,215) = .0146*830;
R(215,216) = .0219*700;
R(216,217) = .1037*360;
R(216,218) = .0219*435;
R(211,219) = .0146*25;
R(219,220) = .1633*1170;
%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%% Feeder 294 %%%%%%
R(92,221) = .0517*40;
R(221,222) = .0517*2490;
R(222,223) = .0517*290;
R(223,224) = .0514*250;
R(224,225) = .0514*3520;
R(223,226) = .0517*980;
R(226,227) = .0514*580;
R(226,228) = .0517*360;
R(228,229) = .0517*710;
R(229,230) = .0517*540;
R(230,231) = .0517*160;
R(231,232) = .0517*1170;
R(232,233) = .051*70;
R(233,234) = .2622*70;
R(232,235) = .051*1030;
R(235,236) = .051*130;
R(236,237) = .051*530;
R(237,238) = .051*190;
R(238,239) = .051*420;
```

```
R(239,240) = .051*1470;
R(240,241) = .051*320;
R(241,242) = .051*150;
R(242,243) = .051*200;
R(243,244) = .051*350;
R(244,245) = .051*1920;
R(245,246) = .254*640;
R(246,247) = .254*320;
R(247,248) = .254*5440;
R(248,249) = .254*240;
R(249,250) = .254*1460;
R(250,251) = .254*1862;
R(251,252) = .254*250;
R(252,253) = .254*740;
R(253,254) = .254*280;
R(245,255) = .051*1420;
R(255,256) = .0822*1320;
R(256,257) = .0822*1460;
R(257,258) = .0822*300;
R(258,259) = .0822*720;
R(242,260) = .051*640;
R(260,261) = .051*640;
R(261,262) = .051*80;
R(262,263) = .1633*140;
R(262,264) = .051*100;
R(264,265) = .051*105;
R(262,266) = .051*360;
R(266,267) = .051*460;
R(261,268) = .0514*60;
R(268,269) = .0514*220;
R(269,270) = .0514*120;
R(270,271) = .0514*680;
R(271,272) = .0514*195;
R(272,273) = .0514*180;
R(273,274) = .0514*240;
R(274,275) = .0514*60;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%% Make R symmetric %%%%%%%%

for i = 1:buses
    for j = i:buses
        R(j,i) = R(i,j);
    end;
end;

%%%%%% Calculate Bases %%%%%%%%%

R = 2*R/1000/Rbase;

%%%%%%%%%% CREATING LOAD MATRIX %%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%% Main Substation %%%%%
Pload(1) = 24.3;    %Bus 2
P_locations(1) = 2;
Pload(2) = 24.3;    %Bus 9
P_locations(2) = 9;
%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%% Feeder 116S %%%%%%
Pload(3) = 16.9;    %Bus 20
P_locations(3) = 20;
Pload(4) = 1.7;    %Bus 22
P_locations(4) = 22;
Pload(5) = 1.8;    %Bus 25
```

```
P_locations(5) = 25;
Pload(6) = 159.6;    %Bus 26
P_locations(6) = 26;
Pload(7) = 13.1;    %Bus 27
P_locations(7) = 27;
Pload(8) = 23.6;    %Bus 29
P_locations(8) = 29;
Pload(9) = 33.6;    %Bus 30
P_locations(9) = 30;
Pload(10) = 1.8;    %Bus 32
P_locations(10) = 32;
Pload(11) = 6;    %Bus 33
P_locations(11) = 33;
Pload(12) = 48.8;    %Bus 36
P_locations(12) = 36;
Pload(13) = 81.8;    %Bus 39
P_locations(13) = 39;
Pload(14) = 145.3;    %Bus 42
P_locations(14) = 42;
Pload(15) = 15.0;    %Bus 43
P_locations(15) = 43;
Pload(16) = 1.8;    %Bus 48
P_locations(16) = 48;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%% Feeder 118 %%%%%%%%%%%%
Pload(17) = .2;    %Bus 52
P_locations(17) = 52;
Pload(18) = 35;    %Bus 53
P_locations(18) = 53;
Pload(19) = 64.2;    %Bus 54
P_locations(19) = 54;
Pload(20) = 17.5;    %Bus 58
P_locations(20) = 58;
Pload(21) = 34.9;    %Bus 70
P_locations(21) = 70;
Pload(22) = 570.4;    %Bus 73
P_locations(22) = 73;
Pload(23) = 279.4;    %Bus 75
P_locations(23) = 75;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Substation 901 %%%%%%%%
Pload(24) = 78.2;    %Bus 80
P_locations(24) = 80;
Pload(25) = 6.5;    %Bus 81
P_locations(25) = 81;
Pload(26) = 335.1;    %Bus 84
P_locations(26) = 84;
Pload(27) = 6.7;    %Bus 89
P_locations(27) = 89;
Pload(28) = 6;    %Bus 92
P_locations(28) = 92;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 216 %%%%%%%%
Pload(29) = 165;    %Bus 104
P_locations(29) = 104;
Pload(30) = 212.8;    %Bus 106
P_locations(30) = 106;
Pload(31) = 262.1;    %Bus 107
P_locations(31) = 107;
Pload(32) = 558.8;    %Bus 108
P_locations(32) = 108;
Pload(33) = 3.9;    %Bus 109
P_locations(33) = 109;
Pload(34) = 266.6;    %Bus 111
P_locations(34) = 111;
Pload(35) = 368.2;    %Bus 113
```

```
P_locations(35) = 113;
Pload(36) = 266.6;    %Bus 116
P_locations(36) = 116;
Pload(37) = 368.2;    %Bus 117
P_locations(37) = 117;
Pload(38) = 190.5;    %Bus 118
P_locations(38) = 118;

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%% Feeder 294 %%%%%%%%
Pload(39) = 175.1;    %Bus 122
P_locations(39) = 122;
Pload(40) = 13.4;    %Bus 128
P_locations(40) = 128;
Pload(41) = 445.8;    %Bus 130
P_locations(41) = 130;
Pload(42) = 13.7;    %Bus 132
P_locations(42) = 132;
Pload(43) = 251.4;    %Bus 137
P_locations(43) = 137;
Pload(44) = 290.9;    %Bus 138
P_locations(44) = 138;
Pload(45) = 290.9;    %Bus 139
P_locations(45) = 139;
Pload(46) = 290.9;    %Bus 140
P_locations(46) = 140;
Pload(47) = 290.9;    %Bus 141
P_locations(47) = 141;
Pload(48) = 290.9;    %Bus 142
P_locations(48) = 142;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%% Feeder 334 %%%%%%%%
Pload(49) = 95.3;    %Bus 147
P_locations(49) = 147;
Pload(50) = 17.0;    %Bus 148
P_locations(50) = 148;
Pload(51) = 53.4;    %Bus 151
P_locations(51) = 151;
Pload(52) = 54.74;    %Bus 152
P_locations(52) = 152;
Pload(53) = 34.5;    %Bus 153
P_locations(53) = 153;
Pload(54) = 190.7;    %Bus 156
P_locations(54) = 156;
Pload(55) = 258.5;    %Bus 158
P_locations(55) = 158;
Pload(56) = 258.5;    %Bus 159
P_locations(56) = 159;
Pload(57) = 125.7;    %Bus 166
P_locations(57) = 166;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%% Feeder 214-224 %%%%%%%%
Pload(58) = 638.4;    %Bus 176
P_locations(58) = 176;
Pload(59) = 638.4;    %Bus 178
P_locations(59) = 178;
Pload(60) = 256.5;    %Bus 182
P_locations(60) = 182;
Pload(61) = 101.6;    %Bus 183
P_locations(61) = 183;
Pload(62) = 97.0;    %Bus 184
P_locations(62) = 184;
Pload(63) = 837.5;    %Bus 185
P_locations(63) = 185;
Pload(64) = 409.1;    %Bus 186
P_locations(64) = 186;
```

```
Pload(65) = 601.5;    %Bus 187
P_locations(65) = 187;
Pload(66) = 6;    %Bus 169
P_locations(66) = 169;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 116N %%%%%%%%
Pload(67) = 3729.1;    %Bus 192
P_locations(67) = 192;
Pload(68) = 148.3;    %Bus 193
P_locations(68) = 193;
Pload(69) = 222.4;    %Bus 194
P_locations(69) = 194;
Pload(70) = 105.9;    %Bus 195
P_locations(70) = 195;
Pload(71) = 148.3;    %Bus 197
P_locations(71) = 197;
Pload(72) = 148.3;    %Bus 198
P_locations(72) = 198;
Pload(73) = 285.9;    %Bus 199
P_locations(73) = 199;
Pload(74) = 1.8;      %Bus 203
P_locations(74) = 203;
Pload(75) = 638.4;        %Bus 207
P_locations(75) = 207;
Pload(76) = 638.4;        %Bus 210
P_locations(76) = 210;
Pload(77) = 871.2;        %Bus 212
P_locations(77) = 212;
Pload(78) = 464.4;        %Bus 213
P_locations(78) = 213;
Pload(79) = 180.2;        %Bus 214
P_locations(79) = 214;
Pload(80) = 33.1;        %Bus 217
P_locations(80) = 217;
Pload(81) = 101.6;        %Bus 218
P_locations(81) = 218;
Pload(82) = 1.3;        %Bus 220
P_locations(82) = 220;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%% Feeder 234 %%%%%%%%%%%
Pload(83) = 6.9;        %Bus 225
P_locations(83) = 225;
Pload(84) = 1.4;        %Bus 227
P_locations(84) = 227;
Pload(85) = 69.4;        %Bus 234
P_locations(85) = 234;
Pload(86) = 102.5;        %Bus 248
P_locations(86) = 248;
Pload(87) = 3.2;        %Bus 249
P_locations(87) = 249;
Pload(88) = 7.3;        %Bus 253
P_locations(88) = 253;
Pload(89) = 44.9;        %Bus 254
P_locations(89) = 254;
Pload(90) = 4.1;        %Bus 255
P_locations(90) = 255;
Pload(91) = 38.7;        %Bus 259
P_locations(91) = 259;
Pload(92) = 3.7;        %Bus 263
P_locations(92) = 263;
Pload(93) = 14.0;        %Bus 264
P_locations(93) = 264;
Pload(94) = 1.7;        %Bus 265
P_locations(94) = 265;
Pload(95) = 112.0;        %Bus 267
P_locations(95) = 267;
Pload(96) = 60.9;        %Bus 269
```

```
P_locations(96) = 269;
Pload(97) = 68.8;        %Bus 270
P_locations(97) = 270;
Pload(98) = 6.6;        %Bus 271
P_locations(98) = 271;
Pload(99) = 5.0;        %Bus 272
P_locations(99) = 272;
Pload(100) = 35.1;        %Bus 273
P_locations(100) = 273;
Pload(101) = 16.9;        %Bus 275
P_locations(101) = 275;

%%%%%%%%% DC-DC Converters %%%%%%%

Pload(102) = load1/1000;
P_locations(102) = 277;
Pload(103) = load2/1000;
P_locations(103) = 278;
Pload(104) = load3/1000;
P_locations(104) = 281;
Pload(105) = load4/1000;
P_locations(105) = 282;
Pload(106) = load5/1000;
P_locations(106) = 204;
Pload(107) = load6/1000;
P_locations(107) = 173;
Pload(108) = load7/1000;
P_locations(108) = 283;
Pload(109) = load8/1000;
P_locations(109) = 284;
Pload(110) = load9/1000;
P_locations(110) = 61;
Pload(111) = load10/1000;
P_locations(111) = 62;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

exclude = [61, 62, 137, 173, 192, 204, 277, 278, 281, 282, 283, 284];
loads = length(Pload);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

generator_bus = 12
plosses = load_flow(generator_bus,gen_max, buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff);
toc

Total_losses = (losses1 + losses2 + losses3 + losses4 + losses5 + ...
    losses6 + losses7 + losses8 + losses9  + plosses*Pbase)/1000;

disp(' ')
disp(' ')
disp('Total Losses (kW)')
fprintf('\n%6.2f\n\n',Total_losses)
```

```matlab
function [Plosses,Pgeneration] = load_flow_final(buses, swing_bus, Pload, P_locations,...
        Pbase, R, exclude, eff)

       % Assume initial voltage for all buses = 1 pu
        % Assume initial voltage for all buses = 1 pu
        Pgen =  zeros(1,buses);
        Pload_pu = zeros(1,buses);
        v_bus = ones(1,buses);

        % Bus type 1 is swing, 2 is load, 3 is constant gen
        % Assume all bus types are 2 other than swing and gen
        bus_type = ones(1,buses)*2;

        for a = 1:length(swing_bus)
            bus_type(swing_bus(a)) = 1;
        end;

        % Subtract from load the amount of generation if gen is on load bus
        Pload2 = Pload;


        for a = 1:length(Pload) % Add efficiency losses
            if (find(exclude == a))
                Pload_pu(P_locations(a)) = Pload2(a)*1000/Pbase;
            else
                Pload_pu(P_locations(a)) = Pload2(a)*1000/Pbase/eff(1);
            end;
        end;

        for i = 1:length(exclude)
            Pload_pu(exclude(i)) = Pload_pu(exclude(i))*eff;
        end;


        %%%%%%%%%%% CALCULATE ADMITTANCE MATRIX %%%%%%%%%%%%%%
        for i =1:buses
            for k = 1:buses
                if i ~= k
                    if (R(i,k)) == 0
                        Y(i,k) = 0;
                    else
                        Y(i,k) = -1/(R(i,k));
                    end;
                else
                    Y(i,i) = 0;
                end;
            end;
        end;

        for i = 1:buses
            Y(i,i) = -sum(Y(:,i));
        end;



            z = 0;
            count = 0;
            while (z == 0)
            count = count + 1;

            %%%%% DETERMINE DELTA P VS V %%%%%%%%

            for i = 1:buses
                for k = 1:buses
                    if i ~= k
                        DeltaP_V(i,k) = - v_bus(i)*Y(i,k);
                    else
                        for l = 1:buses
                            DeltaP_V_sum(l) = v_bus(l)*Y(i,l);
```

```
                    end;
                    DeltaP_V(i,i) =  -sum(DeltaP_V_sum)-v_bus(i)*Y(i,i);
                end;
            end;
        end;

        %%%%%%%%%%% CREATE JACOBIAN %%%%%%%%%%%%%%%

        j_position = 1;
        for i = 1:buses
            i_position = 0;
            if bus_type(i) == 2
                for k = 1:buses
                    if bus_type(k) == 2
                        i_position = i_position + 1;
                        J(i_position,j_position) = DeltaP_V(k,i);
                    end;
                end;
                j_position = j_position+1;
            end;
        end;

   %%%%%%%%%%%%%%%%%  FIND DELTA P %%%%%%%%%%%%%%%%%%
        count = 1;
        for i=1:buses
            if bus_type(i) == 2
                for k=1:buses
                    sum_P(k) = v_bus(k)*Y(i,k);
                end;
                b(count) = Pgen(i)-Pload_pu(i)-v_bus(i)*sum(sum_P);
                count = count + 1;
            end;
        end;

   %%%%%%%%%%%%%%%%% SOLVE LINEARIZED EQUATION FOR DELTA X %%%%%%%%%%%%%%%%%%
        deltaV = inv(J)* -b';

        if deltaV < .0001
            z == 1
        elseif count > 50
            z == 1
        end;

        count = 1;
        for i=1:buses
            if  bus_type(i) == 2
                v_bus(i) = v_bus(i) + deltaV(count);
                count = count + 1;
            end;
        end;

        v_bus;

    end;

  % Determining Net Injection
for i = 1:buses
    for k = 1:buses
       Pinj_sum(k) = v_bus(k)*Y(i,k);
    end;
    Pinj(i) = v_bus(i)*sum(Pinj_sum);
end;

% Determining generation at each bus
for i=1:buses
    Pgen_inj(i) =  Pinj(i) + Pload_pu(i);
end;

% Determining net losses
```

```
Plosses = sum(Pgen_inj)  - sum(Pload2*1000/Pbase);


% Determining generation at swing
Pgeneration = Pgen_inj(swing_bus);

% Determining losses in each given line
for i = 1:buses
    for j = 1:buses
        if R(i,j) == 0
            P(i,j) = 0;
        else
            P(i,j) = (v_bus(i)^2-v_bus(i)*v_bus(j))/R(i,j);
        end;
    end;
end;
```

VITA

Michael Starke received his B.S. and M.S. Eletrical Engineering degrees from the University of Tennessee in 2004 and 2006. He has worked for the Oak Ridge National Laboratory in various positions since 2005. His interests are focused on power system applications in areas such as DC systems, renewable energy sources, and protection. During his spare time, he enjoys bike riding and ballroom dancing with his wife. He is currently employed by Oak Ridge National Laboratory.